Under what Circumstances will Permanent Carbon Forestry with the added benefit of Native Restoration become More Favourable than Rotational Carbon Forestry

A dissertation submitted in partial fulfilment of the requirements for a Bachelor of Forestry Science with Honours

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Abstract

Long-term financial modelling was undertaken to determine under what circumstances permanent carbon forestry with the added benefit of native restoration would become more favourable than rotational carbon forestry.

The literature noted a distinct lack of long term radiata pine (*Pinus radiata*) nurse crop data available in New Zealand. The use of *Pinus* nurse crops for indigenous restoration has shown promise both in New Zealand and abroad. Canopy gap creation within a pine stand has been found to be one of the most effective strategies for transitioning pine stands into native forests provided browsing ungulates are excluded and there is a viable seed source nearby.

In this study, permanent carbon forestry was found to be more economically viable than rotational carbon forestry. This is the case on all sites when the permanent carbon forest is unthinned. The profitability of permanent carbon forestry in comparison to rotational carbon forestry increases with carbon price. Rotational carbon forestry becomes more competitive with permanent carbon forestry as carbon price and Total Delivered Wood Cost (TDWC) decrease and log price and site productivity increase.

The managed transitional strategy chosen to achieve native restoration, be it canopy gap creation followed by passive native regeneration or underplanting, has a Net Present Value (NPV) significantly less than that of permanent or rotational carbon forestry. However, under an exceptionally low log price, transitioning a radiata pine forest to a native forest will be more profitable than managing it as a rotational forest.

Where canopy gap creation followed by underplanting is required due to the absence of a viable seed source, this will not significantly affect NPV. If a landowner desires a truly permanent native forest, canopy gap creation or underplanting within a radiata pine carbon nurse crop can achieve this while still making a return on the landowner’s investment.

As a result, it is paramount the new permanent forestry activity to be implemented as part of New Zealand’s Emissions Trading Scheme (ETS) allows for canopy gap creation to transition permanent carbon pine forests to native forests to better deliver on the climate change mitigation, environmental, social and economic goals of the One Billion Trees Programme and ETS.

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Chop it!

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1. Introduction

1.1 Background

In 2008 the New Zealand government implemented the Emissions Trading Scheme (ETS) as a mechanism to help the nation meet its legally binding obligations under the first commitment period of the Kyoto protocol (Ministry for the Environment [MfE], Kyoto Protocol, 2019). As part of this protocol, New Zealand pledged to limit greenhouse gas (GHG) emissions to the 1990 levels on average from 2008-2012 (MfE, Kyoto Protocol, 2019). Although New Zealand did meet its obligations, through carbon sequestration provided by plantation forests during the first commitment period, in 2009, the new National government decided New Zealand would not commit to the second period of the Kyoto Protocol from 2013-2020 (MfE, Kyoto Protocol, 2020).

The ETS resembles a ‘cap-and-trade’ system where one New Zealand Unit (NZU) is equal to one metric tonne of carbon dioxide equivalent (tCO_2e) sequestered or released from the atmosphere (MfE, ETS, 2019). A forester can receive NZUs from the government for the carbon sequestered by post-1989 forest land (Te Uru Rākau, Forest Land, 2020). Today the ETS is still used to enable New Zealand to meet its new climate change commitments under the 2016 Paris Agreement which will apply to New Zealand from 2021 (Te Uru Rākau, ETS, 2020).

Forestry will be a major driver in New Zealand’s climate change mitigation efforts moving forward. To improve the effectiveness, accessibility and administration of the ETS, the Climate Change Response (Emissions Trading Reform) Amendment Act 2020 has been passed into law (MfE, ETS Reforms, 2020). This includes significant improvements for forestry’s involvement in the ETS, most notably;

- Increase of the fixed carbon price cap from $25/NZU to $35/NZU for 2020,
- Implementation of auctioning with a carbon price floor of $20/NZU and cap of $50/NZU (2021),
- Introducing average accounting for all newly registered post-1989 forests (2023),
- Replacement of the Permanent Forest Sink Initiative (PFSI) with a new post-1989 permanent forest activity (2023) (Ministry for Primary Industries [MPI], ETS Improvements, 2020).

These reforms will make both permanent and rotational carbon forestry an even more attractive investment. The addition of carbon trading cashflows under the ETS has been found to significantly increase the Net Present Value (NPV) and Land Expectation Value (LEV) of rotational forestry investments (Maclaren, et al, 2008; Manley & Maclaren, 2012). Forestry investments have typically been evaluated at a base carbon price of $25/NZU (the previous cap and average market price) with profitability and optimum rotation age increasing as higher carbon prices were evaluated. The introduction of the 2020 $35/NZU cap ($50/NZU from 2021) and the $20/NZU floor (preventing the carbon price from dropping below $20/NZU) has already had a significant effect on the market carbon price. The current average carbon price is at or near the cap of $35/NZU (OMF Financial, 2020) (Appendix A). The market is also anticipating the carbon price to increase above this cap when it is lifted in 2021 (OMF Financial, 2020). This will have serious implications for the profitability of forestry investments and land use change in the future. The introduction of average accounting has also improved profitability under the ETS without the need to take on carbon price risk for all forest growers, regardless of size (Manley, 2020).

High carbon prices are also more likely to delay the optimum rotation age of rotational forests established under the ETS to earn more carbon credits, possibly to an extreme point where a permanent forest is incentivised (Maclaren, et al, 2008; Manley & Maclaren, 2012; Manley, 2020). This will be especially true on poor sites where harvest is costly. Adding the opportunity for these forests to be recognised as permanent under the ETS stock change accounting and earn more NZU, beyond that of average accounting, makes this an attractive option for forest investors.

In addition to the ETS, the New Zealand Government announced the One Billion Trees programme (1BT) in 2018 to further improve environmental, social and economic outcomes for regional New Zealand. Through this programme, the government hopes to encourage the planting of one billion trees in New Zealand by 2028 (MPI, 1BT, 2020). With less than eight years to go, almost 250 million trees have been planted and the government is one quarter of the way to achieving its goal (MPI, Tree Tracker, 2020).

1.2 Purpose

Climate change and deforestation are the most important issues facing the human population today. There is scientific consensus on the record levels of ever-increasing anthropogenic GHG emissions in our atmosphere. Trees offer an opportunity to act as carbon sinks by removing the GHG CO_2 from the atmosphere through the process of photosynthesis.

In 2018, New Zealand's total gross GHG emissions were 78.9 million tCO_2e (MfE, GHG Inventory, 2020). The forestry sector removed 23.4 million tCO_2e of this from the atmosphere, representing a 30% offset and leaving New Zealand with net emissions of 55.5 million tCO_2e for 2018 (MfE, GHG Inventory, 2020). In 2018, New Zealand's 1.7 million ha of exotic forest biomass carbon was estimated to be 292 million tCO_2e (MfE, GHG Inventory, 2020). This is in addition to over 2 billion tCO_2e carbon stored by 8 million ha of native forest biomass (MfE, GHG Inventory, 2020).

As well as storing carbon, New Zealand's native forests provide habitats for globally unique flora and fauna. Approximately 85% of New Zealand's land area was covered by native forest before human settlement (Kimberley, Bergin, & Beets, 2014). Approximately one third of this was lost during deforestation after Māori arrival sometime during the 13th century (Kimberley, Bergin, & Beets, 2014). A further one third was lost after continued deforestation by European settlers starting in the 1800s to leave New Zealand with just 24% of its land area left in native forest cover (Kimberley, Bergin, & Beets, 2014).

Early isolation from the terrestrial mainland 80 million years ago has left New Zealand with approximately 80% of birds and plants, 90% of freshwater fish and 100% of frogs, reptiles and bats as endemic species; not including those already extinct (Meurk & Hall, 2006). Therefore, forest habitat for these unique remaining species must be conserved and enhanced to ensure the survival of these species that can be protected nowhere else in the world.

Recently in New Zealand there has been tensions around the encroachment of exotic plantation forestry onto land that has traditionally been used for other land uses such as sheep and beef farming. Anti-forestry lobby groups are unhappy with afforestation rates under the ETS and 1BT and claim these government programmes incentivise the planting of exotic pines rather than establishing native forests. Many media outlets have recently pushed the narrative that afforestation of exotic pine plantations is not more beneficial for the environment than establishing native forests (Chalmers, 2019; Eder, 2019). This supports long-standing assumptions that pine plantations are ‘biological deserts’ where nothing grows in ‘wall to wall wood’. In reality, native species biodiversity is often greater under pine forest than other land uses in New Zealand (Brockerhoff, et al, 2008).

1BT incentivises tree planting through a range of afforestation grants (Appendix B) (Te Uru Rākau, Direct Grants, 2020). The base rate for native planting starts at $4,000/ha compared to just $1,500/ha for exotic planting (Te Uru Rākau, Direct Grants, 2020). Even with the $4,000/ha grant, native forestry projects often fail to recover the high costs of their establishment. Exotic species such as radiata pine (*Pinus radiata*) had been previously favoured under 1BT and the ETS due to their low cost of establishment, faster growth leading to higher carbon stocks at early ages and the added potential for timber revenues. Previously, 88% of trees established under 1BT grants were exotic species. However, recently the government has responded to these criticisms and as of 2020, 58% of trees established under the 1BT grants are natives (MPI, Tree Tracker, 2020).

The motto of 1BT is “right tree, right place, right purpose” (MPI, 1BT, 2020). In congruence with these words, this dissertation aims to evaluate if the New Zealand public can have the best of both worlds. That is the rapid early carbon sequestration, low establishment costs and high carbon stocks of exotic pines acting as a nurse crop coupled with the longevity and environmental and social benefits of long-term native restoration. This dissertation will also look at where this strategy would be economically competitive with rotational forestry to best deliver on the environmental, social, economic and climate change mitigation goals of the ETS and 1BT throughout New Zealand.

1.3 Analysis

This dissertation will involve long-term financial modelling to evaluate under what circumstances permanent carbon forestry with the added benefit of native restoration will become more favourable than rotational carbon forestry. Rotational carbon forestry modelling will be conducted across combinations of site productivity and Total Delivered Wood Cost (TDWC) to represent forests around New Zealand and make comparisons with permanent carbon forestry. This dissertation will also look at market factors such as log and carbon price and how this will affect the NPV of these forestry investments. Preference will mainly be determined by the economics (NPV) of these two investments. However, landowner objectives will also be discussed to determine when they may choose permanent or rotational forestry.

For the purpose of this dissertation; permanent carbon forestry will be defined as post-1989, radiata pine plantation forestry established and managed to maximise carbon sequestration and NZUs earned under the ETS stock change accounting approach and which cannot be clearfelled for 50 years. These forests have the opportunity to become nurse crops for native restoration at older ages. This definition is designed to align with that of MPI for the new permanent forestry activity beginning in 2023 (MPI, ETS Improvements, 2020). Rotational carbon forestry will be defined as post-1989, radiata pine plantation forestry established under the ETS and earning NZUs under the average accounting approach but managed primarily for the production of wood products.

Native tree species are unlikely to establish and grow effectively under a pine stand without some form of management intervention (Forbes, et al, 2015, 2016, 2019). As a result, for the transition from a pine forest to a permanent native forest, several managed and unmanaged scenarios and will be explored. These include;

- Periodically thinning the pine stand using canopy gap creation to assist passive native regeneration, assuming there is a viable seed source nearby.
- Underplanting of successional native species within the same canopy gap regime to ensure establishment for native regeneration.
- A windthrow scenario where a significant proportion of pine canopy trees are windthrown, allowing passive native regeneration to occur.
- A senescence scenario where the pine canopy is seriously degraded by a pest or pathogen, allowing passive native regeneration to begin.

The economics and effectiveness of each of these transitions from an exotic pine plantation to a native forest will be evaluated and compared to rotational forestry.

1.4 Research questions

This dissertation contains three main research questions:

1. Will permanent carbon forestry be more economically viable than rotational carbon forestry under any combination of site productivity and TDWC difficulty or under any likely log and carbon prices?
2. Will the managed transitional strategy chosen to achieve native restoration have an NPV significantly less than that of permanent or rotational carbon forestry under any combination of site productivity and TDWC difficulty or under any likely log and carbon prices?
3. Will the managed transitional strategy chosen to achieve native restoration significantly affect NPV?

2. Literature Review

2.1 Old growth pine stands

In New Zealand, radiata pine plantations typically have a rotation age of 25-30 years depending on site productivity and market factors (Lewis & Ferguson, 1993; Woollons & Manley, 2011). However, managing forests under the ETS for carbon as well as wood production could extend the rotation age to 40-50 years or older depending again on site productivity, discount rate and regime choice (Maclaren, et al, 2008; Park, et al, 2012 Woollons & Manley, 2011). This effect can be taken to the extreme under high carbon prices when the rotation age of a forest established under the ETS may be delayed so far into the future that a permanent rather than a rotational forest is incentivised to continue growth and sequester more carbon (Manley, 2020).

Another reason plantation forests may not be harvested in New Zealand is because it is simply not physically feasible or economically viable to do so. During the high log prices of the 1990s there was rapid investment in small-scale, privately-owned (woodlot) forestry (MPI, NEFD, 2019) (Appendix C) which created a 'wall of wood' consisting of exceptionally high harvest volumes which the industry is now experiencing as these forests have matured (PF Olsen, 2020). Many plantation forests in New Zealand, particularly those established by small-scale owners during the 1990s planting boom, may not have been planted with the foresight of harvest viability (Park, et al, 2012). The National Exotic Forest Description (NEFD) defines a small-scale forest as one of less than 40 ha in size and are often owned and established by private landowners rather than being part of a large company's forest estate (MPI, NEFD, 2019). Small-scale forests in New Zealand may not be harvested for a variety of reasons including steep terrain making harvesting and roading too difficult and excessive transport distances to market (Ministry of Agriculture and Forestry, 2010; Park, et al, 2012). The small-sized nature of these forests in of itself can also make harvesting less profitable as harvest cost increases with decreasing forest size (Raymond, 2012). Forests can also be left unharvested for a wider range of environmental, social or economic factors (Forbes, et al, 2015, 2016, 2019). Whatever the reasoning may be, there are forests in New Zealand that are left unharvested (Woollons & Manley, 2011).

When planted in botanic gardens radiata pine is known to survive for at least 150 years (Woollons & Manley, 2011). Woollons & Manley (2011) found that there were only 140 Permanent Sample Plots (PSPs) in New Zealand that were maintained and measured for at least 50 years. In Mount Gambier, South Australia there is limited evidence of sustained growth of radiata pine out to age 50 (Leech, 1978). In Chile, the majority of radiata pine plantations are recently established or are privately-owned with no longevity publications (Lewis & Ferguson, 1993). In East Africa, radiata pine is a minority species and lacks quality data (Lewis & Ferguson, 1993). The distinct lack of data noted in the literature (Leech, 1978; Lewis & Ferguson, 1993; Woollons & Manley, 2011) indicates that clear-felling of radiata pine plantation forests for wood products at an optimum rotation age occurs well before these forests get the chance to become nurse crops both here and abroad. However, the radiata pine PSP data available in Woollons & Manley (2011) shows no sign of senescence at age 50 with stands in excess of 60-100 years being viable.

2.2 Pine nurse crops

Forbes, et al (2015, 2016, 2019) have extensively studied the potential for pine stands to act as nurse crops for native regeneration in New Zealand. The concept of pine stands functioning as nurse crops through suppression of light-demanding weeds, protection from weather extremes and partial shading for shade-tolerant species is well documented as a means to encourage regeneration into a successional, permanent, native forest (Allen, et al, 1995; Brockerhoff, et al, 2003; Forbes, et al, 2015, 2016, 2019; Norton & Forbes, 2013; Ogden, et al, 1997).

A study by Forbes, et al (2019) noted the following. Approximately 70% of New Zealand native plant species are predominately dispersed by birds. As a result, nearby seed sources are important to ensure undergrowth of natives if no underplanting is performed due to *Pinus* *spp.* not being able to attract native avifauna with fruit or nectar. The chronosequence of radiata pine stands aged 2-89 years in this study showed these forests became more effective at acting as a nurse crops with age. These plantations could support readily dispersed native regeneration although not as well as a geographically and climatically similar indigenous forest reference site and lacked the presence of any long-lived native podocarp species which are important for a healthy forest composition and structure. These species may take 30-60 more years to establish. It is theorised that although native podocarp seeds may be present in pine understoreys, the canopies lack the disturbance regimes necessary to encourage their establishment. As a result, management interventions are recommended to mimic disturbance and achieve successful forest succession.

Another pine nurse crop study by Forbes, et al (2016) also noted the following. Interventions such as artificial canopy gap creation can mimic disturbance regimes and provide shelter and additional photosynthetically active radiation to maximize native regeneration under pine stands. In many cases, without intervention, understorey composition indicative of natural regeneration can take 15-20 years to form plus several more decades before indigenous canopy species become established. Underplanting of both tōtara (*Podocarpus totara*), a light-demanding, and tawa (*Beilschmiedia tawa*), a shade tolerant native species in both large and small manufactured canopy gaps in an 18-year-old radiata pine stand resulted in prolific regeneration of these species compared to when no canopy gaps were created. Gap size can be varied to cater to the light requirements of specific species. For example, tōtara regeneration is observed to be most successful within the larger gap sizes. The elimination of ungulates is vital for the success of native regeneration under a pine canopy as canopy gaps may increase incidence of animal browse and resulting seedling mortality.

Underplanting of rimu (*Dacrydium cupressinum*), tōtara and kahikatea (*Dacrycarpus dacrydioides*) stands within a 36-year-old ponderosa pine (*Pinus ponderosa*) stand that had been heavily degraded by the *Dothistroma pini* fungal pathogen was also studied by Forbes, et al (2015). This underplanting achieved a podocarp dominated forest structure within 50 years. Tōtara and kahikatea stands had a carbon stock (tCO_2/ha/year) not significantly less than that of the pine stand while the underplanted rimu stand had a carbon stock significantly higher than the pine overstorey. Rimu was the most dominant species with the largest basal area and all three native podocarp species had greater stand densities (stems/ha) than the declining 87-year-old ponderosa pine trees.

The ability of the *Pinus* genus to act as a nurse crop for native vegetation has been similarly documented overseas. *Pinus caribaea* plantations in sub-tropical North Queensland, Australia showed increases in indigenous tree species richness with age (Keenan, et al, 1997). In the temperate Ethiopian highlands, seed dispersal from adjacent native forests encouraged late successional species to establish under *Pinus patula* plantations (Senbeta, et al, 2002). Much like New Zealand plantations, mature radiata pine stands have likewise shown potential for facilitating native regeneration of *Quercus spp.* in Spain (Onaindia & Mitxelena, 2009; Onaindia, et al, 2013). Creating canopy gaps within *Pinus* plantations has also proven to be an effective method for restoration of indigenous forests internationally. In tropical Sri Lanka, removal of rows of *Pinus caribaea* enabled the growth of underplanted successional species (Ashton, et al, 1997). Canopy gap creation in *Pinus sylvestris* plantations in Finland advanced the dominance of regenerating indigenous understorey species, aiding restoration (Rouvinen & Kouki, 2011). In Japan, circular gaps in a 40-year-old *Pinus thunbergii* plantation were created which promoted forest succession of native seedlings from the understorey (Zhu, et al. 2003).

2.3 Previous modelling

Long term modelling of forest succession under radiata pine has been undertaken previously using LINKNZ (Hall & Hollinger, 2000). Although carbon storage per hectare in native forests may not reach that of radiata pine, native forests still offer an opportunity to store carbon long term as a healthy, successional native forest is unlikely to senesce (Hall, 2001). Modelling over a 500-year period in Christchurch predicted a mixed plantation forest of radiata pine and several native species to reach a peak carbon stock of 550 tCO_2/ha at 80 years (Hall, 2001). The same model predicted native podocarp species to replace the radiata pine over the next 120 years to then become dominated by native tōtara varieties and matai (*Prumnopitys taxifolia*). When compared to a native only model run under the same constraints, the composition of the forest was similar after the pine had senesced although the carbon stock was 20% lower at 400 tCO_2/ha (Hall, 2001). The introduction of exotic radiata pine resulted in an earlier and higher carbon stock peak compared to a purely native forest but this benefit was likely to be outweighed by the lower sustainable carbon stock in the resulting native forest (Hall, 2001).

LINKNZ was used to model 50 forest successions over 800-2,000 years in Auckland, Queenstown and Christchurch (Meurk & Hall, 2006). To explore the possible indigenous component of plantations, after 15 years, 20% of a radiata pine initiated stand was thinned and natives were introduced (Meurk & Hall, 2006). From this point onwards the model would harvest 20% of radiata pine trees with a diameter at breast height (dbh) > 30 cm every 20 years to favour the slow-growing native species (Meurk & Hall, 2006). Under this regime natives became dominant around 150 years and pine was replaced by 200 years (Meurk & Hall, 2006). Dominant native species included a range of native *Beilschmiedia*, podocarp and broadleaved species (Meurk & Hall, 2006).

LINKNZ was also used to model a native only, and radiata pine to native riparian buffer of a hypothetical North Island stream over 800 years (Meleason & Hall, 2005). Senescence of radiata pine occurred within 200 years and was followed by dominance of native conifer species (Meleason & Hall, 2005). Biomass of the transitional forest peaked at 100 years but then declined to a minimum around 250 years indicating the depletion of pine exceeded the recruitment of natives (Meleason & Hall, 2005). In the short term, the pine to native forest produced more biomass than the purely native forest in early successional stages (Meleason & Hall, 2005). However, in the long term, biomass in the purely native forest was slightly higher than the pine to native forest (Meleason & Hall, 2005). This conclusion is similar to that of Hall (2001) aforementioned.

2.4 Final remarks

Although there is little quantitative data available for long term permanent forest transitions from pine to natives, prior research shows promise for non-harvest pine stands to facilitate native regeneration and sequester carbon both in New Zealand and internationally. Those forests around the country that are unlikely to be harvested for a variety of social, environmental or economic reasons have an opportunity to become nurse crops for the regeneration of important native species. Long range modelling predicts when and how forest succession will occur and confirms that pine understorey growth will eventually result in a structurally and compositionally healthy permanent native forest. There are also a variety of management interventions available to achieve this transition present within the literature with canopy gap creation being perhaps the most promising.

3. Methodology and Assumptions

A discounted cashflow analysis financial model was constructed from scratch within Microsoft Excel 2016. This model was used to evaluate permanent and rotational carbon forestry on a range of sites and permanent carbon forestry with and without the added benefit of native restoration over 100 years. The species used for rotational forestry and the permanent forestry nurse crop was radiata pine. All NPV calculations were performed at a discount rate of 8%. This discount rate was used as it was the median response to the question "What discount rate do you use to evaluate new planting investments?" in the 2017 forest valuation survey (Manley, 2018).

3.1 Rotational carbon forestry

The silvicultural regime used for plantation forestry was as follows:

- Plant 1,000 stems/ha
- Thin to waste at stand age 8 to 800 stems/ha
- Thin to waste at stand age 11 to 500 stems/ha.

Rotational carbon forestry was evaluated under an unpruned regime with a rotation age of 28 years, at which all standing trees are clearfell harvested for wood products. Rotational carbon forests were evaluated at three different site and 300 indices representing a low, medium and high productivity site (Table 1). Site index is defined as the mean top height of a radiata pine stand at 20 years of age (Kimberley, et al, 2005). The 300 Index is defined as the mean annual increment of stem volume (m^3/ha/year) for a pruned stand that was thinned at an early age, with a current age of 30 years and a final crop stocking of 300 stems/ha (Kimberley, et al, 2005). Both these indices are commonly used as a measure of site quality for radiata pine plantations throughout New Zealand (Kimberley, et al, 2005).

Table 1: Site and 300 indices used to represent and low, medium and high productivity site for radiata pine forestry in New Zealand

Site Productivity	Site Index	300 Index
Low	26.3	25.8
Medium	30.2	29.0
High	32.6	32.6

In addition to revenue streams from harvesting, rotational forests were also able to earn NZUs under the ETS using average accounting. Under this carbon trading strategy, NZUs based on the annual change in carbon stock were traded annually up to the average carbon stock of the second rotation at each site, provided the forest is replanted (Appendix D). This is the new accounting approach available to newly registered post-1989 forests as of 2019 (MPI, ETS Improvements, 2020).

The silvicultural regime and these site productivities were used as inputs to the Radiata Pine Calculator Version 4.0 Pro (Knowles, 2014). The Radiata Pine Calculator was used to determine the carbon stock (tCO_2e/ha) contained by the forest each year at all three sites as well as the expected yields of each log grade at a 28-year clearfell harvest.

3.2 Log grades and prices

The log grades used include S30, S20, A, KS, KI, KIS and Pulp. These log grades are commonly cut in New Zealand forestry and contain a mix of domestic and export log grades. The addition of the KIS export grade encompasses what would otherwise be a domestic Pulp grade with additional straightness to satisfy the export market. Domestic structural grades, S30 and S20, are assumed to be downgraded and sold as export A and KS grades respectively. As a result, export log prices were assumed.

The prices of these log grades were obtained from AgriHQ. Average monthly AgriHQ $/t nominal log prices from March 2014 to February 2019 for export log grades delivered to the Port of Tauranga and domestic grades delivered to Bay of Plenty/Central Plateau mills were used to best represent log grade prices in New Zealand (AgriHQ, 2014-2019). The conversion between tonnes, m^3 and JAS m^3 is assumed to be 1:1:1 in this analysis. AgriHQ log prices considered to be equivalent to those used in this analysis can be found in Table 2. Nominal AgriHQ monthly log prices were converted to real log prices rebased on the Producer Price Index (PPI) from financial quarter four of December 2019 (=1) (Statistics New Zealand, 2020).

Table 2: Real average monthly $/t AgriHQ log prices used in this analysis

Yield Table Log Grade (Base Price)	Equivalent AgriHQ Log Grade
S30 ($127.57/t)	A30/A40
S20 ($118.32/t)	KS
A ($127.57/t)	A30/A40
KS ($118.32/t)	KS
KI ($109.49/t)	KI
KIS ($101.97/t)	KI - $7
Pulp ($55.45/t)	Pulp (domestic)

The expected yield of each log grade at age 28 could then be multiplied by the respective log price and summed to give the expected revenue of the Total Recoverable Volume (TRV) after clearfell at each site.

3.3 Costs

Costs associated with rotational carbon forestry included establishment and silviculture (Table 3), annual overheads (Table 4) and Total Delivered Wood Cost (TDWC). TDWC was determined by the difficulty of harvesting, extracting and delivering timber to market from a given forest. TDWC difficulty was grouped into three classifications of easy, moderate and hard to represent a range of theoretical forest sites throughout New Zealand. The Visser Costing Model (VCM) was used to determine TDWC for each combination of site productivity and harvest difficulty (Visser, 2020). TDWC is made up of harvesting cost, roading costs and transportation cost.

Harvest difficulty was determined by dominant slope of the terrain. Below approximately 30% slope, ground-based harvesting is achievable. Between approximately 30-50% slope, ground-based harvesting is possible with specialist equipment such as a self-levelling machine or winch assist machine and an experienced operator. Between approximately 50-70% slope, the upper limit of ground-based harvesting operations is reached without the use of winch assist technology. Above approximately 70% slope, cable or helicopter extraction is required. As the slope of terrain increases, so too does the cost and safety concerns of a harvest operation. Roading cost was determined by the roading required within the forest which was assumed to be 28m/ha (Visser, 2020). Roading required from the public road to the forest and existing road needing to be upgraded were also taken into account. Transportation cost was determined by the distance to be travelled on unsealed forest roads and public roads to deliver harvested logs to market (nearest port or mill). The final determinant of TDWC is expected TRV. Harvesting cost, roading cost and as a result, TDWC, decrease with increasing TRV. This is because these costs can be spread over more volume and be less expensive on a $/t basis with higher yields which needed to be accounted for in the analysis.

In addition to these variables; forest size, number of log sorts, fee for road maintenance and number of landings were all kept consistent throughout the different TDWC difficulty sites.

Forest size used to calculate harvest cost was 100 ha as this is the minimum area required to enforce use the Field Measurement Approach (FMA) for calculating carbon stock rather than the MPI Carbon Look-up Tables (Te Uru Rākau, 2018). A forest size of 100 ha would also ensure that a small harvest area would not inflate harvesting costs as small woodlots are more expensive to harvest than larger forest tracts (Visser, 2020). The FMA allows the benefits of factors such as silviculture (high stocking, no pruning) and productivity to be realised rather than using MPI's regionally averaged radiata pine Carbon Look-up Tables (MPI, 2017). Number of log sorts used was seven; consistent with the number of log grades used in this analysis. A fee for road maintenance within the VCM was always assumed to be necessary. The number of landings used was 13 based on an average of one for every 8 ha rounded to the nearest whole number (Visser, 2020). Details of other VCM factors that varied between different TDWC difficulty sites can be found in Table 5.

Table 3: Silvicultural costs used in this analysis for rotational carbon forestry

Year in which cost is incurred for a rotation	**Description**	**Value (NZD/ha)**
0	Land Preparation	$250
0	Planting	$1,100
1	Releasing	$200
8	Thin to waste	$500
11	Thin to waste	$700

Table 4: Total annual overhead and constituent costs used in this analysis for rotational carbon forestry

Description	**Value (NZD/ha)**
Protection	$5
Maintenance	$5
Management	$20
Administration	$10
Insurance	$25
Rates	$15
ETS FMA	$30
Total Annual Cost	**$110**

Table 5: VCM inputs used to determine TDWC difficulty of rotational forestry at an easy, moderate and hard site

	TDWC Difficulty		
VCM Factor	**Easy**	**Moderate**	**Hard**
Harvesting Cost			
Slope	30%	50%	70%
Roading Cost			
Roading in stand			
Existing (m)	0	1,000	500
Required (m)	0	2,800	2,800
Roading to stand			
Existing (m)	0	500	1,000
Required (m)	0	1,000	5,000
New road required			
Hilly/steep terrain	0	1,150	6,300
Flat/rolling terrain	0	1,150	0
Road improvement	2,800	1,500	1,500
Transportation Cost			
Distance on unsealed road (m)	2,800	3,800	7,800
Distance to market (km)	50	125	200

3.4 Permanent carbon forestry

Radiata pine plantations used for permanent carbon forestry were modelled on low, medium and high productivity sites (Table 1). Two permanent carbon forestry scenarios were modelled. The first regime was unthinned, plant and leave 1,000 stems/ha, the same planting density as used for rotational carbon forestry. As a result, the same silvicultural establishment costs as rotational carbon forestry were used minus the thinning costs (Table 3). This represents a perceived scenario of blanket afforestation under high carbon prices. However, plant and leave forestry may result in an unstable forest as high stockings increase susceptibility to windthrow (Knowles & Paton, 1989), the transmission of pests and disease (Munck, et al, 2016) and competition for resources, often leading to earlier senescence. As a result, a more realistic permanent carbon forestry scenario using the same regime as described for rotational carbon forestry (Table 3) was also modelled to directly compare the decision to harvest a structurally thinned forest for wood products or continue earning NZUs through permanent forestry.

The Radiata Pine Calculator Version 4.0 Pro was used to generate the carbon stocks under these scenarios out to age 50. From 50 years onwards, a function developed by Manley

(2020) to extend the MPI Carbon Look-up Tables from 50 to 100 years was used to taper off carbon stock increase out to 100 years as the stability of the Radiata Pine Calculator became compromised after age 50. This function decreased the annual change in carbon stock from age 51-100 by an annually reducing proportion of the change in carbon stock between ages 40 and 50. It was assumed that for all permanent carbon forestry scenarios, NZUs were traded under the stock change accounting approach (Appendix D). Under this carbon trading strategy, NZUs are earned or must be purchased based on the change in overall total carbon stock of the forest each year.

All permanent carbon forestry scenarios that involved regeneration of natives had additional costs associated with them. A fencing cost of $2,217/ha was incurred in the earliest year in which the first native regeneration was expected. This fencing cost was based on the average cost ($/m) to install a 1.9 m high, non-electric deer netting boundary fence (MfE, 2016). It was assumed that 100 m of fencing would be required per hectare. Forbes, et al, (2016) note that the exclusion of browsing ungulates such as deer and grazing animals is vital for the survival of natives established under a pine nurse crop. In addition, permanent carbon forestry scenarios involving native regeneration were also subject to an annual overhead pest control cost of $20/ha (Operational Solutions for Primary Industries, 2017). Otherwise annual overhead costs were the same as for rotational carbon forestry (Table 4).

3.5 Canopy gap creation

A canopy gap creation regime within an unthinned permanent carbon forest was based on one developed by Dr Adam Forbes (2020, personal communication). Canopy gaps modelled were circular with a 6.79 m radius making the canopy gap area 144 m^2. The cost of creating one of these gaps was based on waste thinning and was assumed to be $212.94/ha. This was based on a cost of $145/ha used by Piers Maclaren & Associates Ltd (2004) which was converted to real dollars rebased on the PPI from financial quarter four of December 2019 (=1) (Statistics New Zealand, 2020). This canopy gap creation regime involved periodically removing pines over time and creating favourable conditions for regeneration of native forest naturally or through underplanting. The space and light provided by these canopy gaps aimed to allow natives to take up canopy dominance in the future. The canopy gap creation regime can be found in Table 6.

Table 6: Canopy gap creation used in this analysis for native regeneration through thinning and underplanting

Age	Gaps created	Gaps/ha	Proportion of ha treated	Proportion of pine remaining
12	11	11	16%	84%
17	11	22	32%	68%
22	11	33	48%	52%
27	11	44	64%	36%
32	11	55	80%	20%
37	11	66	96%	4%

Under this thinning scenario, it is assumed there is a viable seed source nearby as this is a critical factor in allowing native species to become established under a radiata pine nurse crop and for native regeneration to occur (Forbes, et al, 2019). The carbon stock of native regeneration within these canopy gaps is based on the MPI Carbon Look-up Tables. The Carbon Look-up Table for indigenous forest is developed from data from areas of regenerating native shrubland rather than regenerating native forest canopy species (MPI, 2017). This is because manuka (*Leptospermum scoparium*) and kanuka (*Kunzea ericoides*) shrubland frequently acts as a nurse crop for other native species and is often the first stage of natural native regeneration (MPI, 2017). This regenerating scrubland accounts for approximately 70% of native regeneration throughout New Zealand (MPI, 2017).

The indigenous look-up table is a national average of carbon stock for a given hectare of land in New Zealand up to an age of 50 years (MPI, 2017) and was assumed to represent a medium productivity site. As a result, the indigenous Carbon Look-up Table was modified based on the pine nurse crop conditions already established allowing faster regeneration of future canopy dominants such as native podocarp species to be possible. These large statured native tree species are more effective at sequestering carbon than native shrubland (Kimberley, et al, 2014). Research suggests that the MPI indigenous Carbon Look-up Tables overestimate carbon stock of regenerating and planted natives by 30-60% under age 20 and underestimate carbon stock by 10-100% after age 40 (Kerr & Craver, 2017). As a result of these differences compared to the type of native regeneration being facilitated in this analysis, the indigenous Carbon Look-up Table was modified based on these findings to accurately represent passively regenerating biomass under a pine nurse crop.

The same function as used for the radiata pine carbon stock, developed by Manley (2020), was used to extend the indigenous look-up table to 100 years of age. An adjustment factor was then used to modify the native carbon stock in each year from the original look-up table based on prior research (Kerr & Craver, 2017; Kimberley, et al, 2014). This carbon stock was used to model all permanent carbon forestry scenarios involving passive native regeneration within canopy gaps including after windthrow and senescence in this analysis. A comparison of the original MPI indigenous forest Carbon Look-up Table and the modified native carbon stock used in this analysis for permanent carbon forestry can be found in Appendix (E).

3.6 Underplanting

Underplanting of native species was modelled within the same gaps created in the regime described in Table 6. The native species to be planted, density and composition is based on that described in Forbes, et al (2015). Planted native species include successional podocarps rimu, tōtara and kahikatea which perform well in restorations throughout New Zealand. Establishment costs for these natives are derived from (Davis, et al, 2009) and can be found in Table 7. Seedlings were assumed to be purchased in soft polythene planter bags (PB2s) to ensure the highest survival rate in transit and during and after establishment (Davis, et al, 2009).

Table 7: Establishment costs of underplanted natives used in this analysis

Establishment cost ($/plant)	**Rimu**	**Tōtara**	**Kahikatea**	**Total**
Seedling (PB2)	$4.00	$2.25	$2.25	
Transportation	$0.60	$0.60	$0.60	
Planting labour	$1.25	$1.25	$1.25	
Weed control at planting	$0.50	$0.50	$0.50	
Total	$6.35	$4.60	$4.60	
Plants per gap	9	14	13	36
Cost per gap	$57.15	$64.40	$59.80	$181.35

Height and diameter data was provided by Dr Adam Forbes from 53 year-old underplanted rimu tōtara and kahikatea in 12.5 ha of degraded ponderosa pine (Forbes, et al, 2015). These measurements were used as input to the Tāne's Tree Trust Carbon Calculator. The survival rate of these underplanted natives within the Tāne's Tree Trust Carbon Calculator was assumed to be 90% given the favourable environmental conditions provided by the radiata pine nurse crop as well as other research (Bergin, 2003; Bergin, et al, 2008; Beveridge et al, 1985; Coomes & Bellingham, 2014; Waring, 2017). These inputs were used to generate the carbon stock sequestered by these natives planted within created canopy gaps on a medium productivity site.

Tāne's Tree Trust Carbon Calculator did not offer the ability to vary outputs by site productivity and the Carbon Look-up Tables were nationally averaged. To model native regeneration on a low and high productivity site, native biomass on a medium productivity site was multiplied by the % change in unthinned pine biomass from a medium to a low and high productivity site given by the Radiata Pine Calculator for permanent carbon forestry. This was done for both passively regenerating and underplanted native biomass (Appendix E) under the assumption that a site that was more or less productive for growing pine trees would be proportionally as productive for regenerating natives.

3.7 Windthrow

Should windthrow occur within an unthinned permanent carbon forest, a scenario was modelled where 50% of a radiata pine permanent carbon forest was windthrown at age 50. From age 50 onwards, natives were modelled to passively regenerate under the remaining radiata pine canopy.

3.8 Senescence

Senescence in a permanent radiata pine carbon forest was modelled using a modification of Manley's (2020) function should early senescence occur in an unthinned permanent carbon forest. Before age 50, growth in radiata pine carbon stock was reduced by an annually increasing proportion of the change in carbon stock between ages 15 and 25. After age 50, this proportion became negative and caused carbon stock to decrease by an annually increasing proportion of the change in carbon stock between ages 30 and 40. This was done to model a possible senescence scenario due to *Dothistroma* fungus or some other pest or pathogen as was documented in Forbes, et al, (2015). From age 50, natives were modelled to begin passive regeneration below the dead standing pine canopy.

3.9 Sensitivity Analysis

Sensitivity analysis was performed on log and carbon price to see how the results would change under different market conditions. Log prices used in sensitivity analysis were determined from trends in real AgriHQ monthly log prices from March of 2014 to February 2020 (Appendix F) (AgriHQ, 2014-2019). The base prices used were the average log grade prices over this period (Table 2). The average base log price was $108/t with a standard deviation of $16/t. Sensitivity of the results to ± 1, 2 and 3 standard deviations from each mean export log price over this period was assessed.

The base carbon price used in the analysis was the current carbon price (as of September 2020) of $35/NZU and current fixed price option ceiling (MPI, ETS Improvements, 2020; OMF Financial, 2020) (Appendix A). Lower carbon price scenarios include $30/NZU, $25/NZU and $20/NZU, the auction reserve price floor from 2021 (MPI, ETS Improveements 2020). Higher carbon price scenarios include $40/NZU, $45/NZU and $50/NZU, the cost containment reserve auction price cap at which point more NZUs will be released into the marketplace to ease demand as of 2021 (MPI, ETS Improvements 2020).

4. Results

4.1 Carbon stock of permanent carbon forestry scenarios

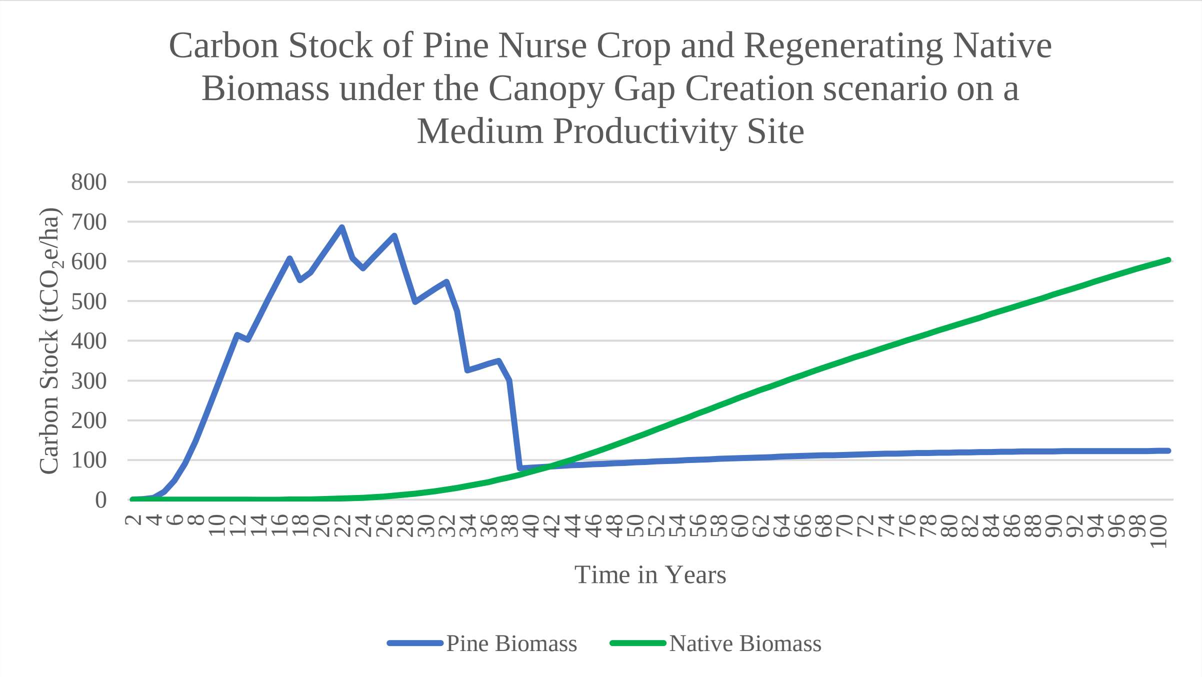

Figure 1: Carbon Stock of pine nurse crop and regenerating native biomass under the canopy gap creation scenario on a medium productivity site

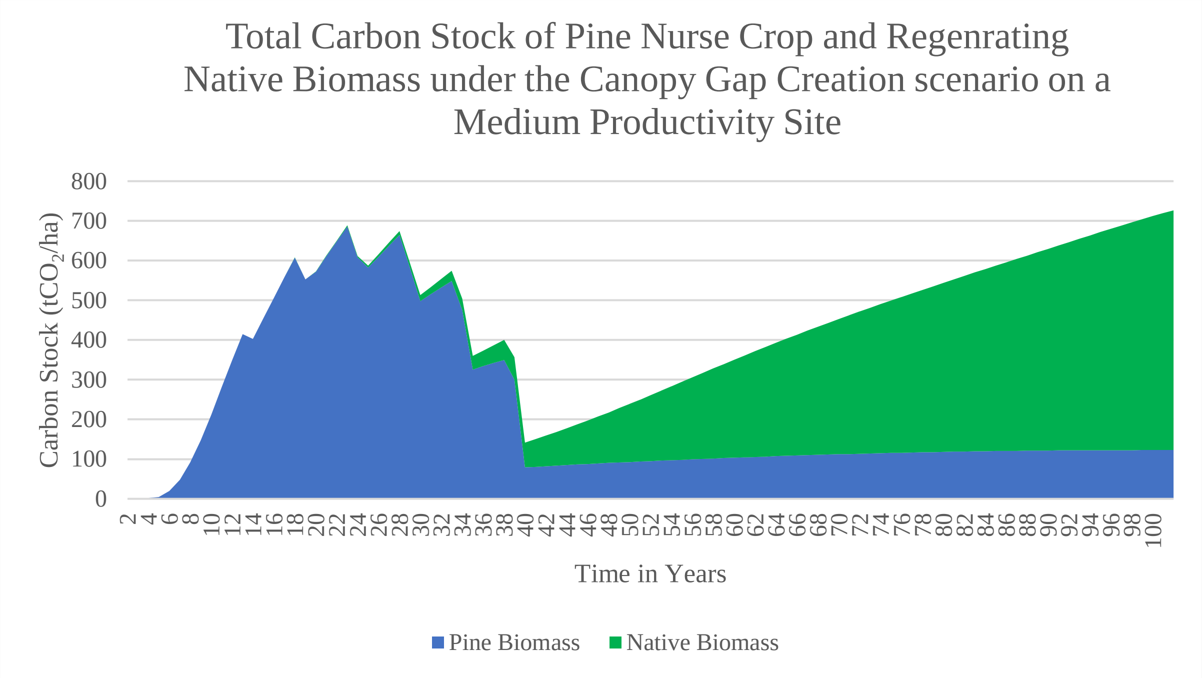

Figure 2: Total carbon stock of pine nurse crop and regenerating native biomass under the canopy gap creation scenario on a medium productivity site

Under the canopy gap creation scenario, pine nurse crop carbon stock rapidly increases initially but reduces more significantly with each successive thinning. After each gap thinning, pine carbon stock begins to increase again although less rapidly with each subsequent thinning. Native regeneration begins once the first canopy gap is created but only starts to have a greater carbon stock than the pine biomass after the final gap thinning around age 42. The maximum carbon stock achieved by the pine biomass is just under 700 tCO_2e/ha. After 100 years the native biomass carbon stock is yet to reach this maximum at just over 600 tCO_2e/ha. At 100 years the pine carbon stock is just over 100 tCO_2e/ha, slightly above what was remaining after the final thinning.

Native biomass does not begin to contribute significantly to total carbon stock under this scenario until after the third gap creation thinning. After this event, the proportion of total carbon stock achieved by regenerating native biomass increases. After the final gap thinning around 50 years, native carbon stock contributes more to the total carbon stock than the remaining pine nurse crop. The contribution of natives towards total carbon stock increases after this point while the contribution of the pine nurse crop remains relatively constant. At 100 years, approximately 85% of the 730 tCO_2e/ha carbon stock is sequestered by native forest.

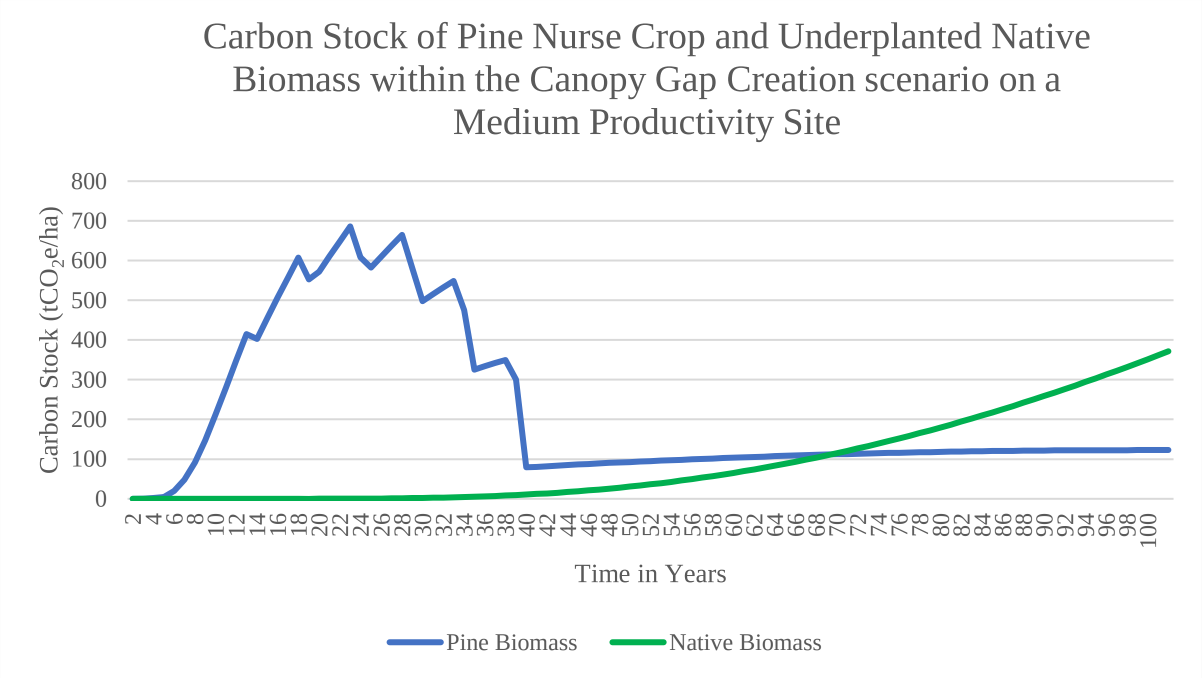

Figure 3: Carbon stock of pine nurse crop and underplanted native biomass within the canopy gap creation scenario on a medium productivity site

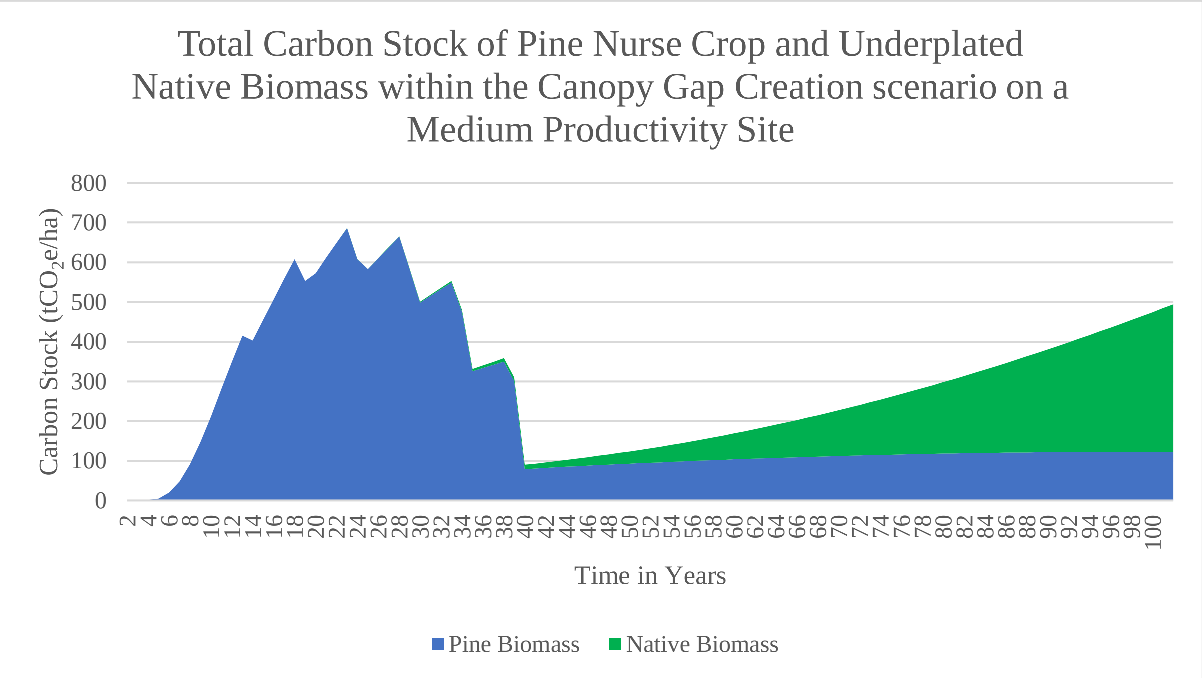

Figure 4: Total carbon stock of pine nurse crop and underplated native biomass within the canopy gap creation scenario on a medium productivity site

When natives are underplanted within these same canopy gaps, regenerating natives are slower to sequester carbon. Native carbon stock only becomes greater than that of the pine nurse crop after 70 years. Natives reach a carbon stock of approximately 370 tCO_2e/ha at 100 years when underplanted.

In terms of total carbon stock, the proportion sequestered by natives does not become more than that of the pine nurse crop until approximately 65 years. After 100 years, the total carbon stock is 500 tCO_2e/ha with less than 80% of this being sequestered by natives. However, the rate of increase in underplanted native carbon stock appears to increase with time to be more rapid than passively regenerating natives in later years. The carbon sequestration of natives underplanted in canopy gaps increases more year-on-year than natives passively regenerating within the same canopy gaps (Figure 2).

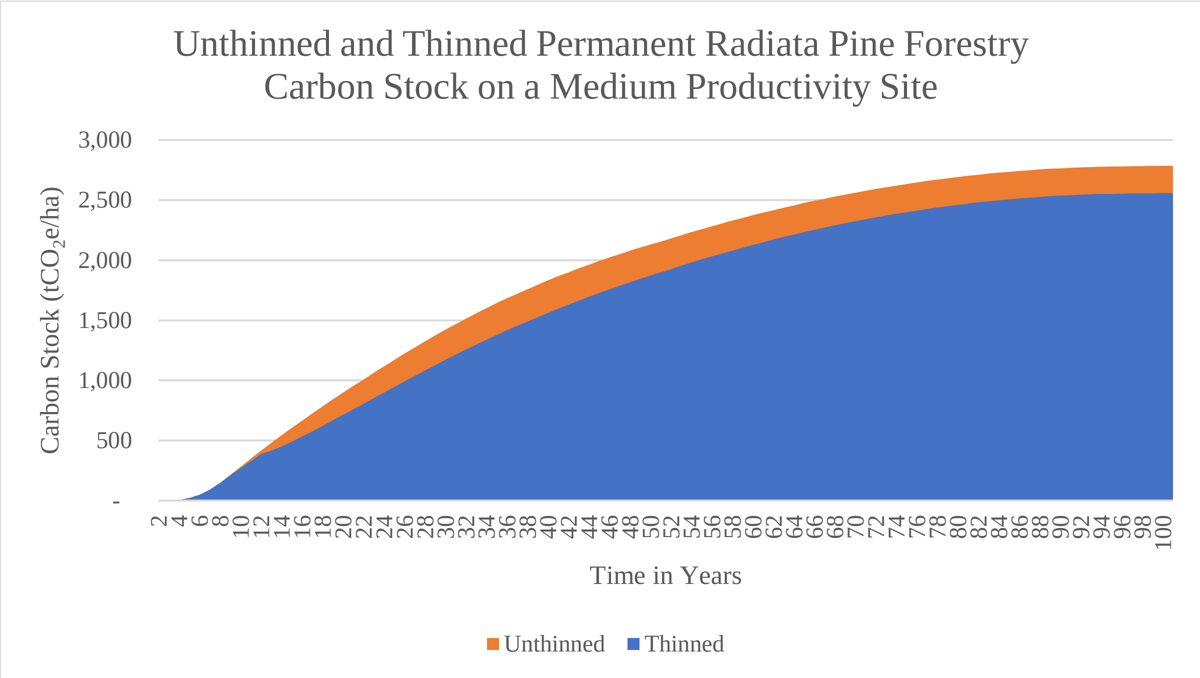

Figure 5: Unthinned and thinned radiata pine forestry carbon stock on a medium productivity site

The carbon stock of permanent radiata pine forestry increases rapidly over 100 years. Significant carbon sequestration begins after 5 years. The increase in carbon stock is rapid initially but decreases with every subsequent year. After 50 years, carbon stock of the unthinned radiata pine is approximately 2,000 tCO_2e/ha. After 100 years the total carbon stock of the unthinned radiata pine is 2,785 tCO_2e/ha. In contrast, the carbon stock of the thinned radiata pine is 2,558 tCO_2e/ha after 100 years. Differences can be seen between the unthinned and thinned carbon stocks after the second structural thinning at 11 years (section 3.1). Both the unthinned and thinned permanent radiata pine forestry carbon stocks are much higher than the carbon stocks achieved by the managed transitional strategies in Figures 2 & 4. After approximately 16 years, permanent radiata pine forestry reaches the same carbon stock as under the canopy gap creation scenario after 100 years.

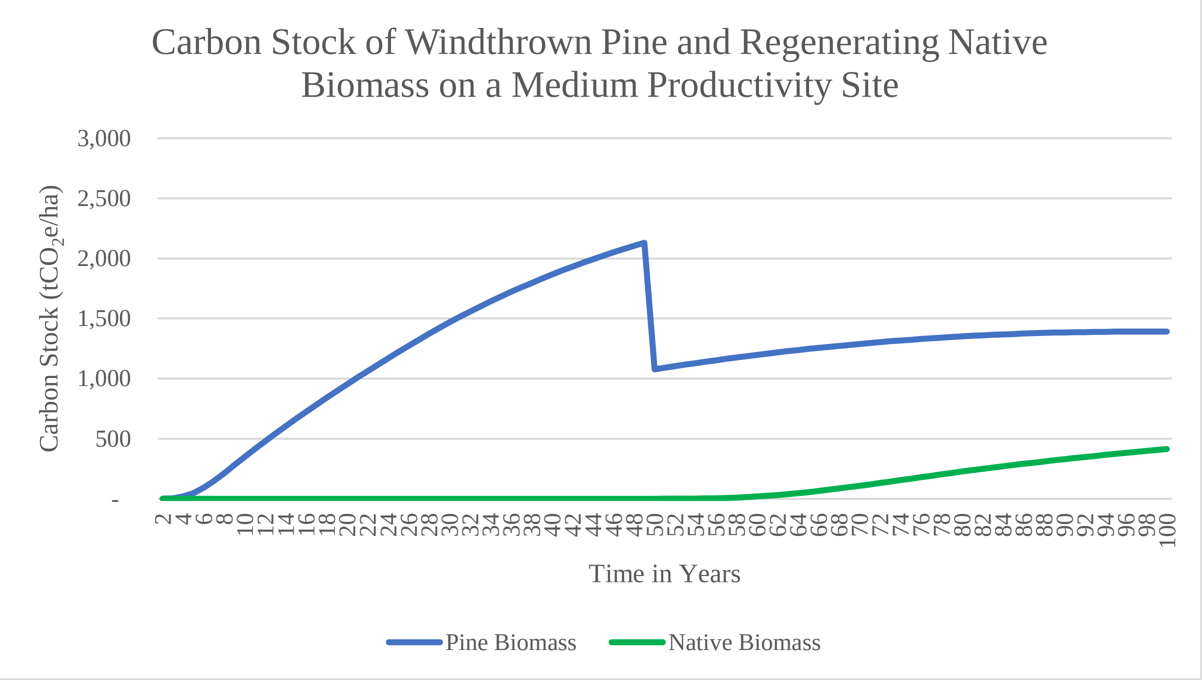

Figure 6: Carbon stock of windthrown pine and regenerating native biomass on a medium productivity site

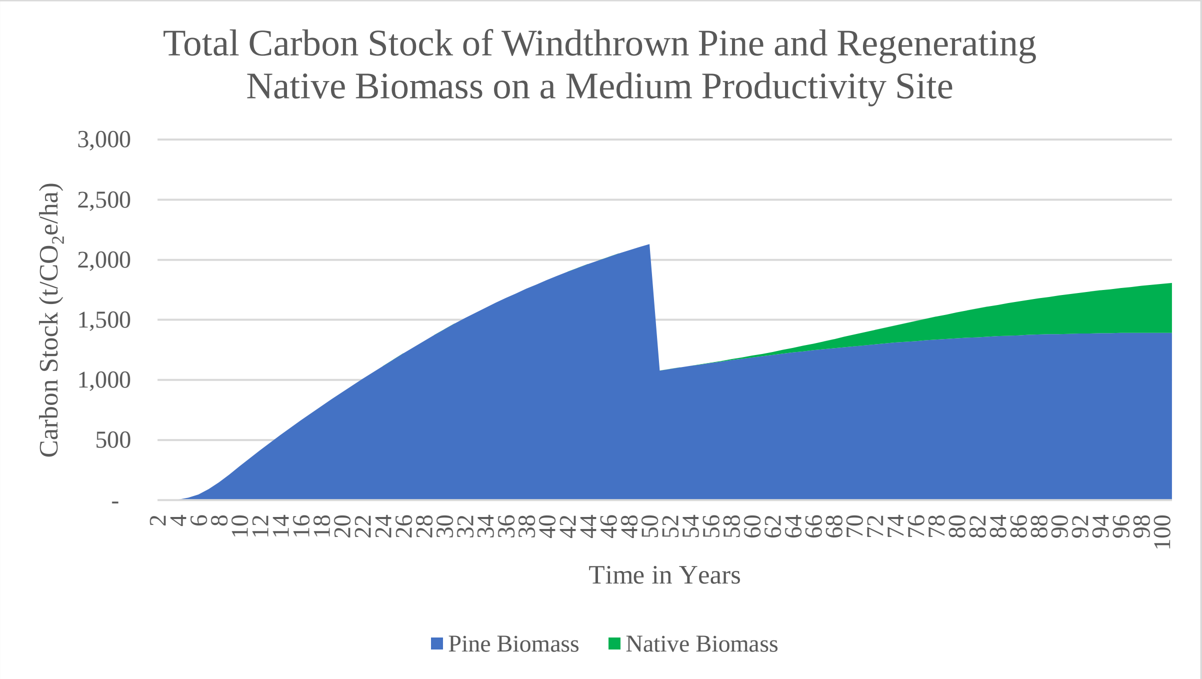

Figure 7: Total carbon stock of windthrown pine and regenerating native biomass on a medium productivity site

Carbon stock of radiata pine peaks at 2,130 tCO_2e/ha at age 49 before the windthrow event is assumed to occur at age 50. This event reduces the pine carbon stock to just over 1,000 tCO_2e/ha. However, the pine carbon stock does increase again slowly after windthrow to approximately 1,400 tCO_2e/ha after 100 years. Passive native regeneration begins after the windthrow event at age 50 and native carbon stock never surpasses that of the windthrown pine within 100 years.

Total carbon stock within the windthrow scenario is buffered by regenerating natives under the remaining pine nurse crop. After 100 years, total carbon stock is approximately 1,800 tCO_2e/ha, 600 tCO_2e/ha more than the windthrown pine carbon stock alone.

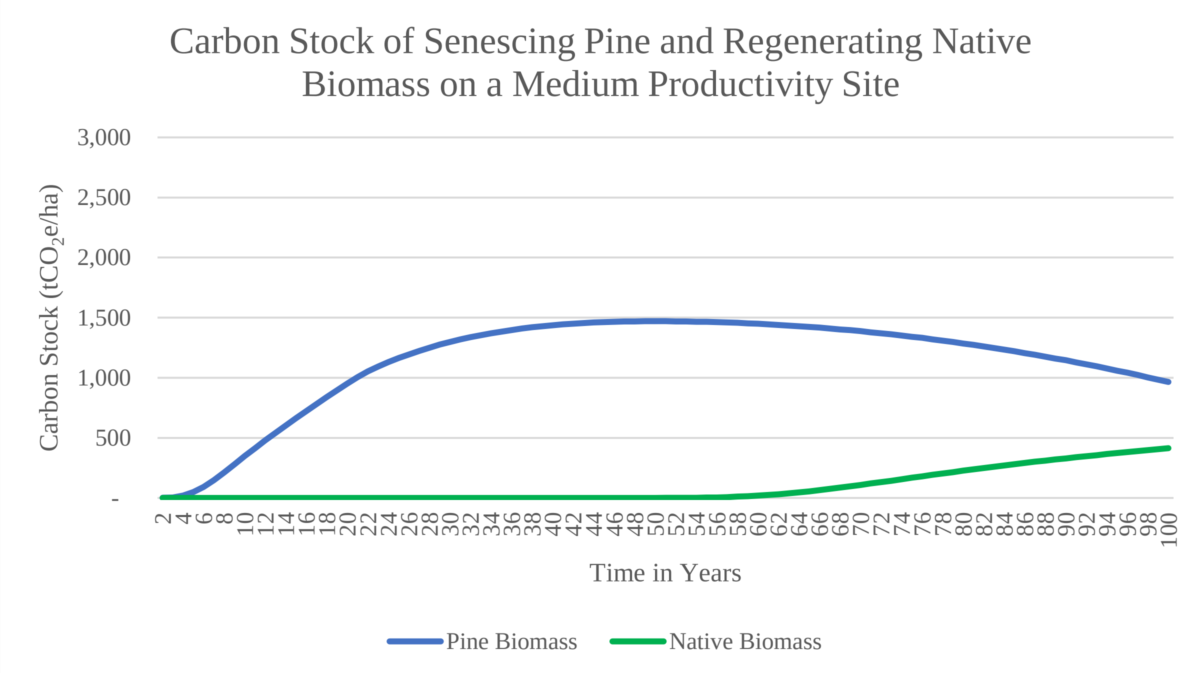

Figure 8: Carbon stock of senescing radiata pine and regenerating native biomass on a medium productivity site

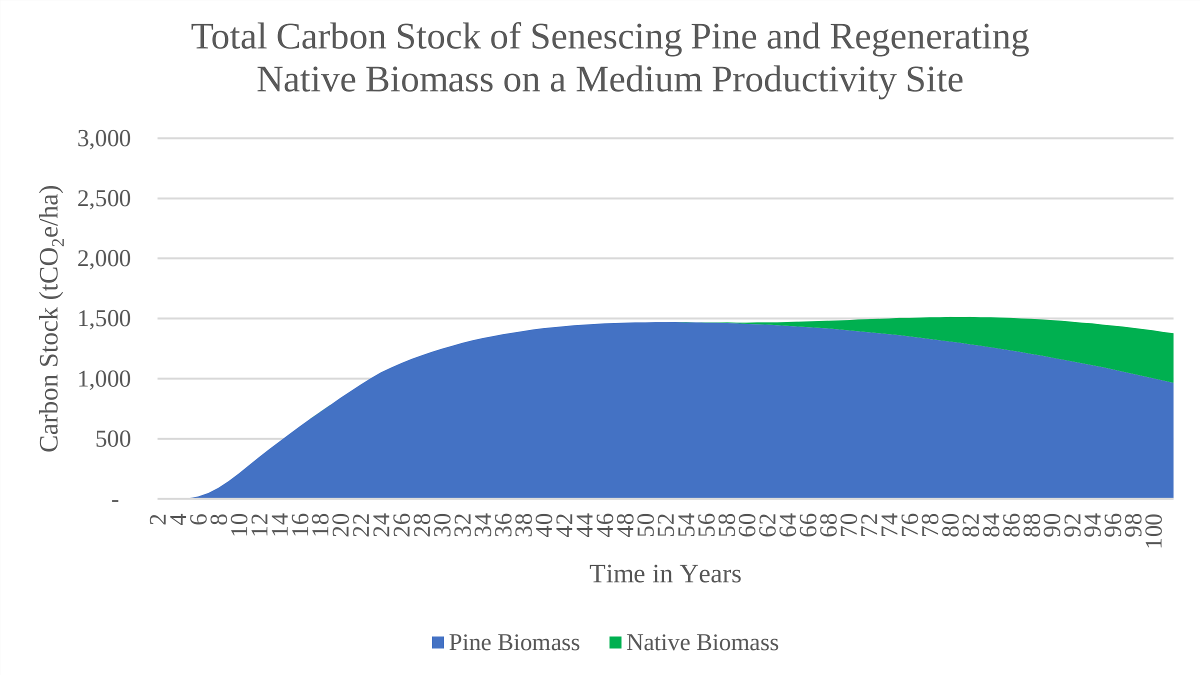

Figure 9: Total carbon stock of senescing pine and regenerating native biomass on a medium productivity site

Radiata pine carbon stock under senescence shows a quadratic trend. The increase in carbon stock is initially rapid until senescence is assumed to begin at age 21. From this point onwards the annual increase in pine carbon stock reduces with time until it becomes negative after age 50. At this point, the pine carbon stock peaks at almost 1,500 tCO_2e/ha. However, as senescence takes hold, pine carbon stock decreases beyond this point to under 1,000 tCO_2e/ha after 100 years. Native biomass begins passively regenerating after age 50 and reaches just over 400 tCO_2e/ha by 100 years, never surpassing the pine carbon stock (same as the windthrow scenario).

In terms of total carbon stock, the native biomass prevents a serious decrease due to the senescing pine. The increasing native carbon stock even allows for a slightly higher, albeit later, peak in total carbon stock of 1,513 tCO_2e/ha at 79 years. After 100 years, total carbon stock including regenerating natives is 1,378 tCO_2e/ha.

4.2 NPV of carbon forestry scenarios

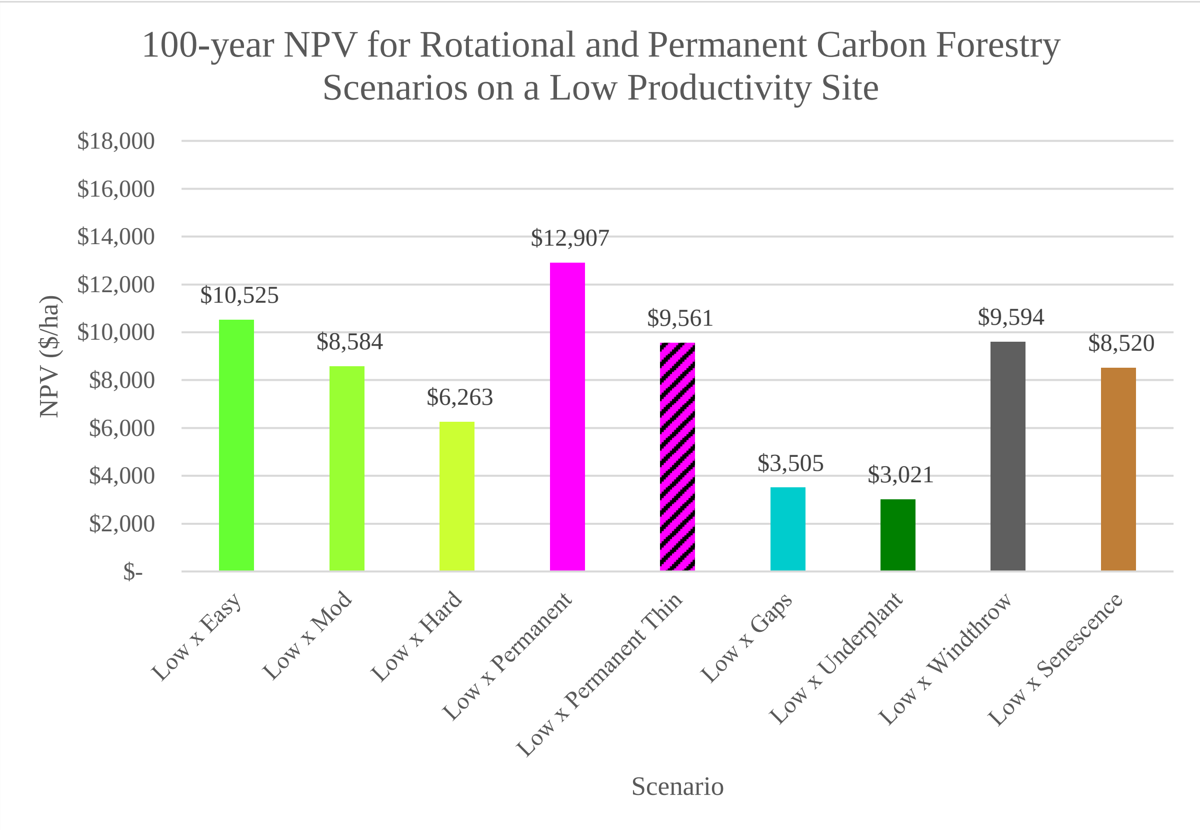

Figure 8: 100-year NPV/ha for rotational and permanent carbon forestry scenarios on a low productivity site at the base log and carbon price

On a low productivity site, the most profitable carbon forestry scenario is permanent carbon forestry with no thinning at just under $13,000/ha. The next most profitable scenario is rotational carbon forestry on an easy TDWC site ($10,525/ha) which is slightly more profitable than the windthrow scenario ($9,594/ha) and permanent carbon forestry with a structural thinning ($9,516/ha). The profitability of rotational forestry decreases as TDWC difficulty increases. The thinned permanent carbon forestry and windthrow scenarios have NPVs approximately $1,000/ha higher than the senescence scenario and rotational forestry on a moderately difficult TDWC site. Rotational forestry on a hard TDWC site has an NPV of $6,263/ha. The two managed transitional strategies to native forestry are the least profitable scenarios with underplanting having an NPV of approximately $500/ha less than simply creating canopy gaps and allowing passive native regeneration within the understorey to occur.

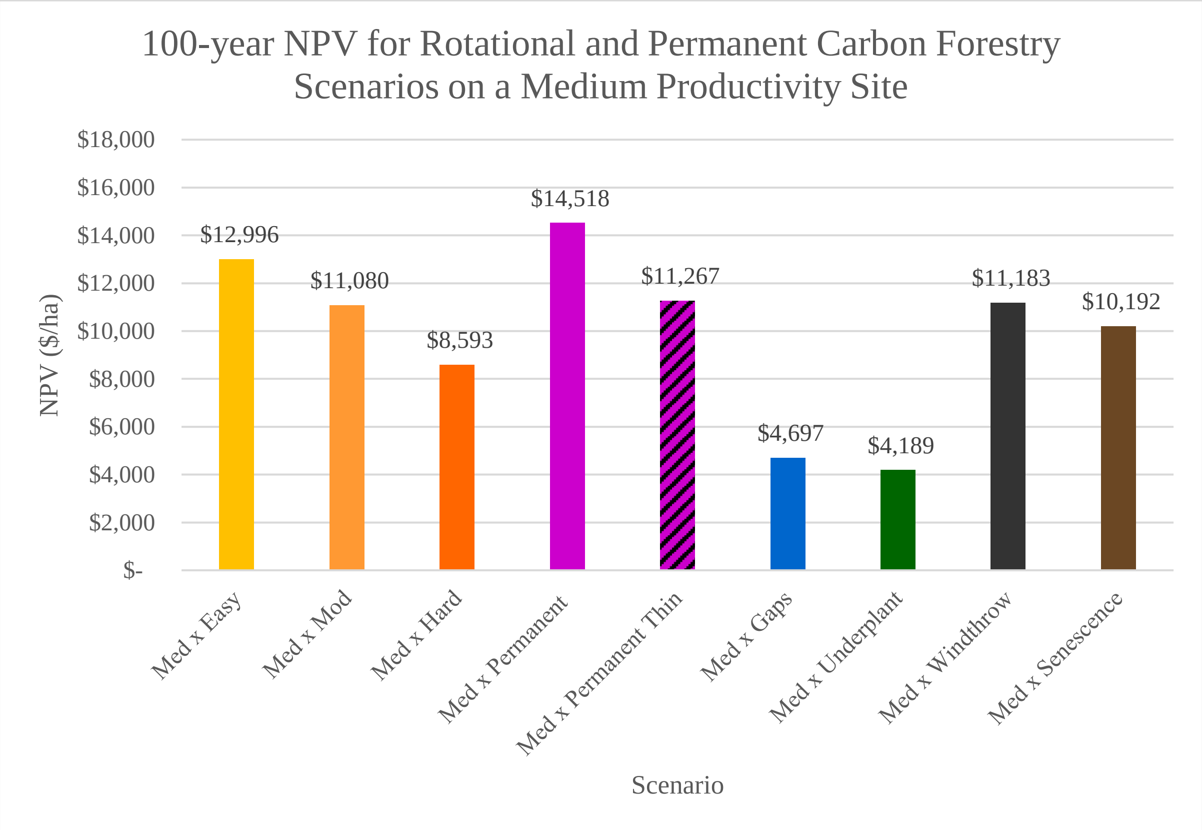

Figure 9: 100-year NPV/ha for rotational and permanent carbon forestry scenarios on a medium productivity site at the base log and carbon price

When these carbon forestry scenarios are implemented on a medium productivity site, profitability rankings remain the same, except thinned permanent carbon forestry becomes more profitable than the windthrow scenario. The NPV of all scenarios increases significantly. The NPV differential between rotational carbon forestry on an easy TDWC site and unthinned permanent carbon forestry is reduced to approximately $1,500/ha on a medium productivity site whereas on a low productivity site the differential between these two scenarios was $2,500/ha (Figure 8). The $1,000/ha NPV differential between the windthrow scenario and moderately difficult TDWC rotational carbon forestry on a low productivity site

(Figure 8) is essentially eliminated on a medium productivity site. These two scenarios have an NPV approximately $1,000/ha higher than the senescence scenario. The NPV of structurally thinned permanent carbon forestry ($11,267/ha) is now closer to that of rotational carbon forestry on a moderate TDWC ($11,080) site rather than approximately $1,000/ha higher as it was on a low productivity site (Figure 8). The NPV of rotational carbon forestry on a hard TDWC site, canopy gap creation with passive native regeneration and underplanting natives within these gaps has increased by $2,330/ha, 1,192/ha and $1,168/ha respectively.

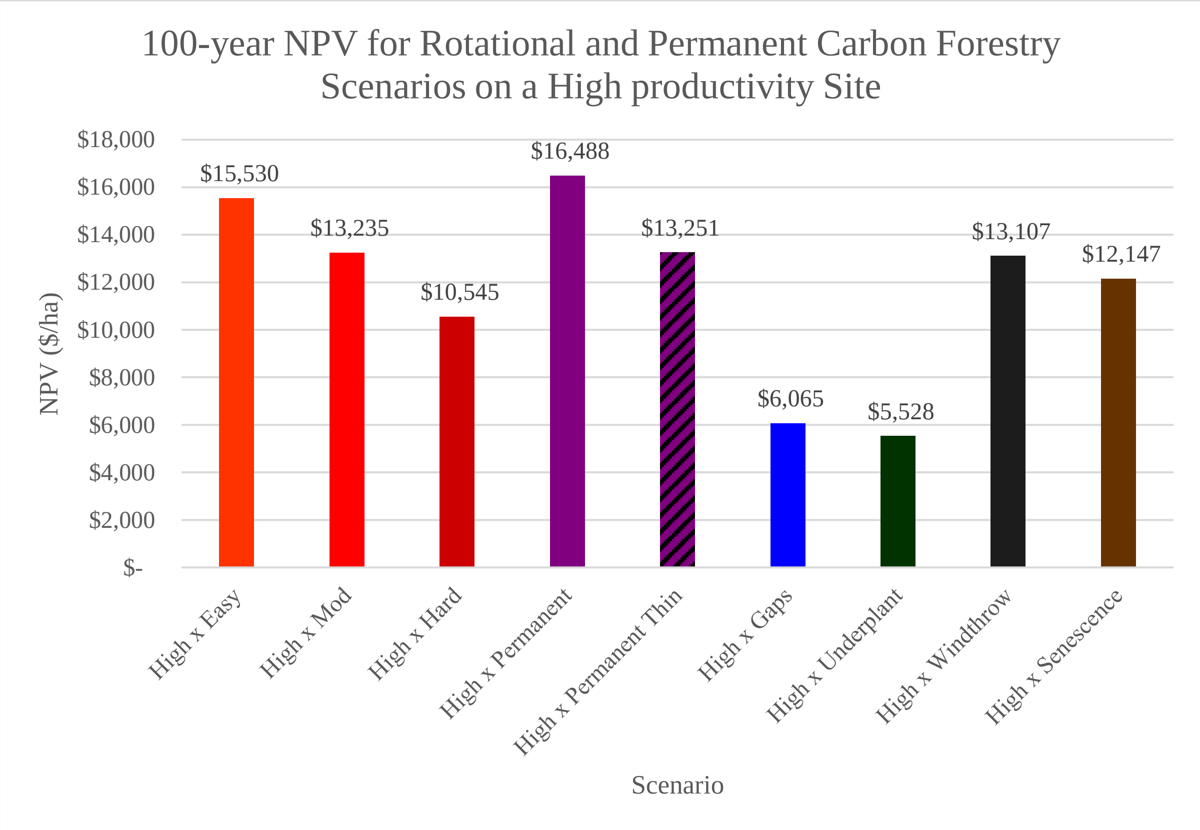

Figure 10: 100-year NPV/ha for rotational and permanent carbon forestry scenarios on a high productivity site at the base log and carbon price

The NPV of these permanent and rotational carbon forestry scenarios again increases significantly when moving from a medium to high productivity site. The NPV differential between rotational carbon forestry on an easy TDWC site and unthinned permanent carbon forestry has again decreased to approximately $1,000/ha on high productivity site. For the first time, the fourth most profitable scenario is rotational carbon forestry on a moderately difficult TDWC site ($13,325/ha) with an NPV higher than both the windthrow and senescence scenarios and much closer to the NPV of thinned permanent forestry on a high productivity site ($13,251/ha). The NPVs of the managed transition scenarios to permanent native forestry through canopy gap creation and underplanting have increased to $6,065/ha and $5,528/ha respectively. However, these scenarios still remain the least profitable options on a high productivity site with NPVs below that of rotational carbon forestry on a hard TDWC site.

4.3 Sensitivity Analysis

4.3.1 Log Price

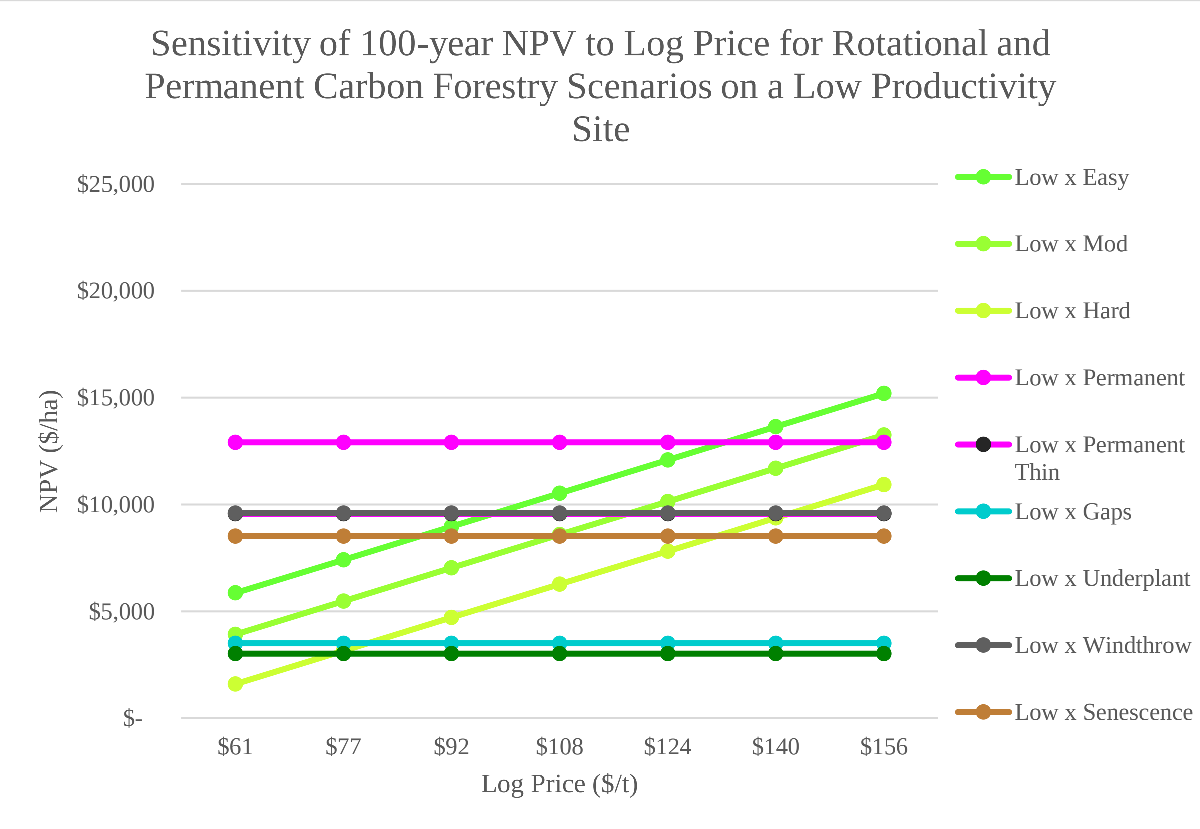

Figure 11: Sensitivity of 100-year NPV to log price for rotational and permanent carbon forestry scenarios on a low productivity site at the base carbon price of $35/NZU

Permanent carbon forestry scenarios are not sensitive to log price while rotational carbon forestry scenarios are highly sensitive to log price. At an average log grade price of approximately $132/t, rotational carbon forestry on an easy TDWC site becomes more profitable than unthinned permanent carbon forestry. At an average log price of approximately $153/t, so too does rotational carbon forestry on a moderately difficult TDWC site. Rotational carbon forestry on all TDWC sites becomes more profitable than the thinned permanent, windthrow and senescence scenarios above an average log grade price of $140/t. At $61/t, canopy gap creation and underplanting of natives are more profitable than rotational carbon forestry on a hard TDWC site. Rotational carbon forestry always has a positive NPV, even on a low productivity site at exceptionally low log prices.

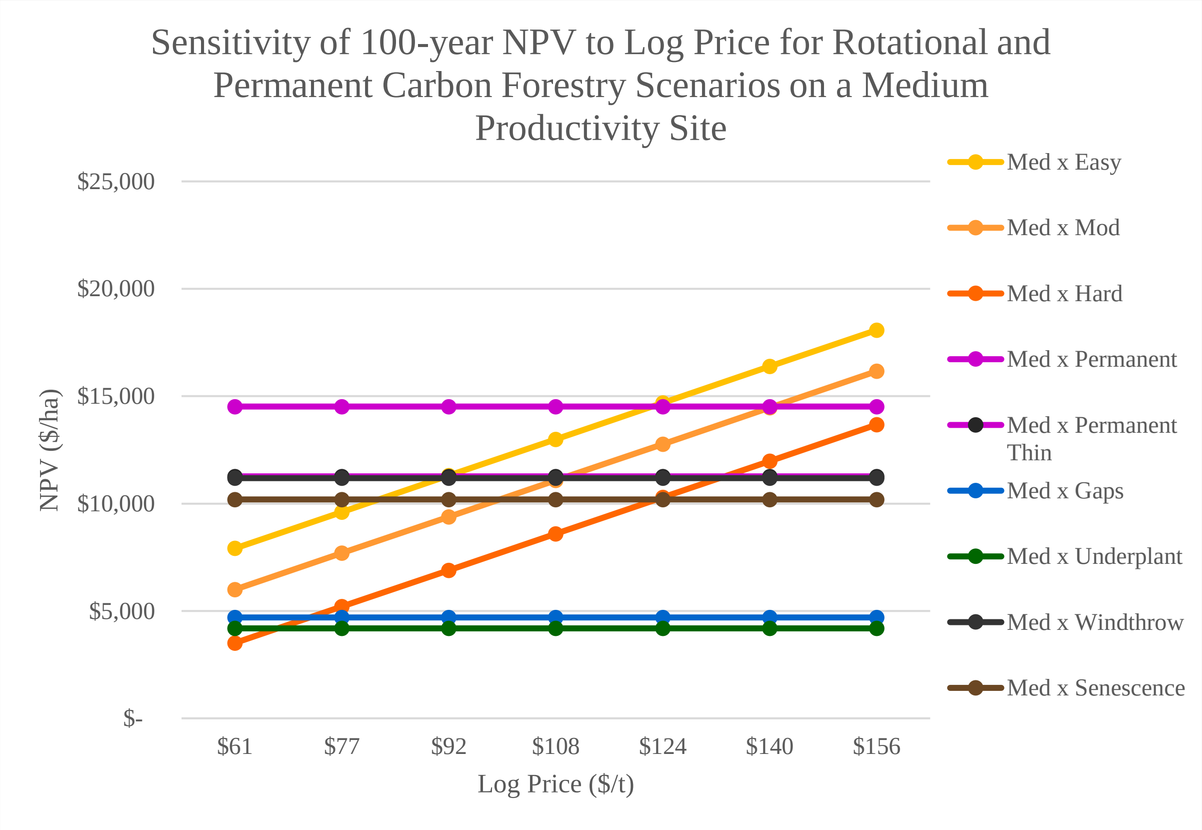

Figure 12: Sensitivity of 100-year NPV to log price for rotational and permanent carbon forestry scenarios on a medium productivity site at the base carbon price of $35/NZU

Similar trends can be seen on a medium productivity site. Rotational carbon forestry on an easy and moderately difficult TDWC site becomes more profitable than unthinned permanent carbon forestry above an average log grade price of $124/t and $140/t respectively. All rotational carbon forestry scenarios have higher NPVs than the thinned permanent, windthrow and senescence scenarios at an average log grade price of approximately $132/t. Rotational carbon forestry on an easy TDWC site has a higher NPV than thinned permanent forestry at $92/t. Managed transitional strategies from native to pine biomass are still more profitable than rotational carbon forestry on a hard TDWC site at $61/t.

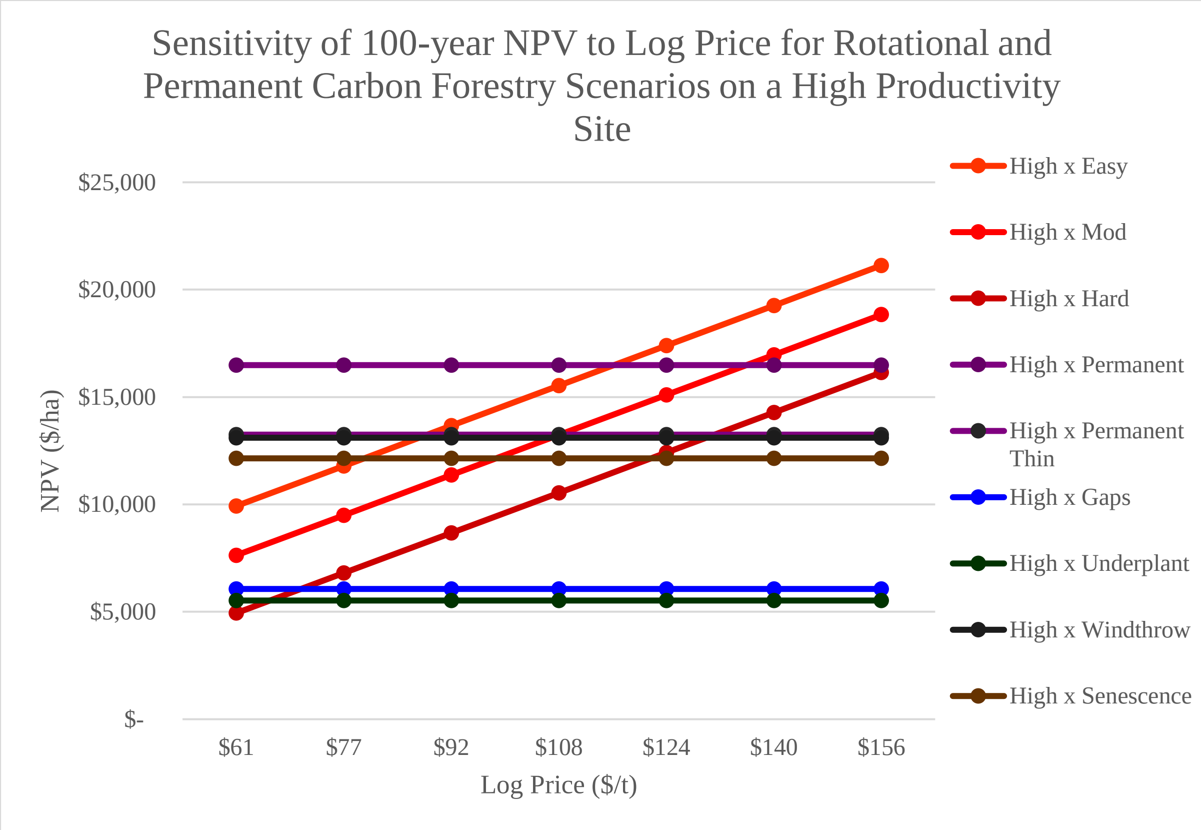

Figure 13: Sensitivity of 100-year NPV to log price for rotational and permanent carbon forestry scenarios on a high productivity site at the base carbon price of $35/NZU

On a high productivity site, rotational carbon forestry on an easy TDWC site becomes more profitable than unthinned permanent carbon forestry at approximately $116/t. All rotational carbon forestry scenarios have an NPV greater than the unthinned permanent, windthrow and senescence scenarios over $128/t. However, at less than $92/t these scenarios having a higher NPV than all rotational carbon forestry scenarios. The managed transitional scenarios are again, still more profitable than rotational carbon forestry on a hard TDWC site at an average log grade price of $61/t.

4.3.2 Carbon Price

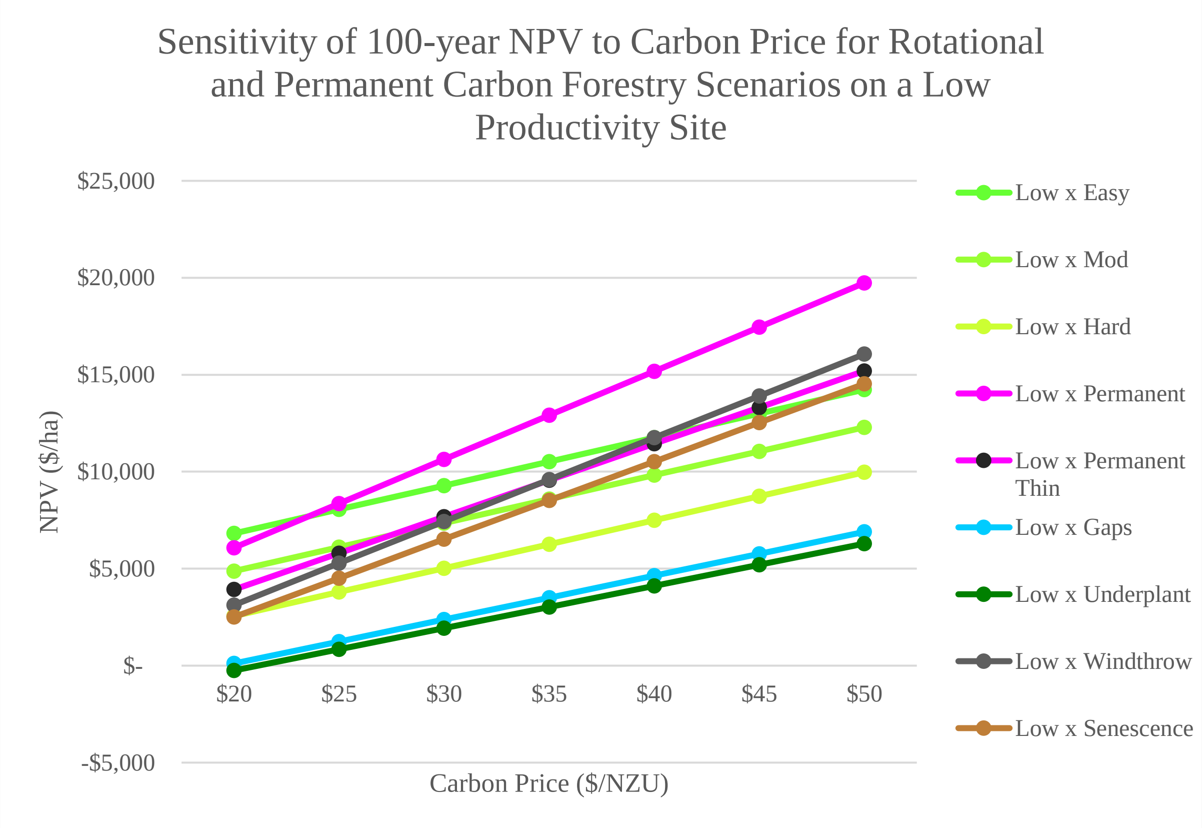

Figure 14: Sensitivity of 100-year NPV to carbon price for rotational and permanent carbon forestry scenarios on a low productivity site at the base log price

On a low productivity site, unthinned permanent carbon forestry is more profitable than rotational carbon forestry, except on an easy TDWC site when the carbon price is below $25/NZU. Thinned permanent carbon forestry and the windthrow scenario are more profitable than rotational carbon forestry even on an easy TDWC site at a carbon price above $42/NZU. The senescence scenario is more profitable than rotational carbon forestry even on an easy TDWC site at a carbon price above $48/NZU. Permanent carbon forestry scenarios, except the managed transitions to natives, are more sensitive to carbon price than the rotational forestry scenarios overall, as shown by the gradients of the lines. Unthinned permanent forestry is slightly more sensitive than thinned permanent forestry to carbon price. The NPV of the gap creation transitional strategy is barely positive at a carbon price of $20/NZU while the NPV of the underplanting in canopy gaps scenario is slightly negative.

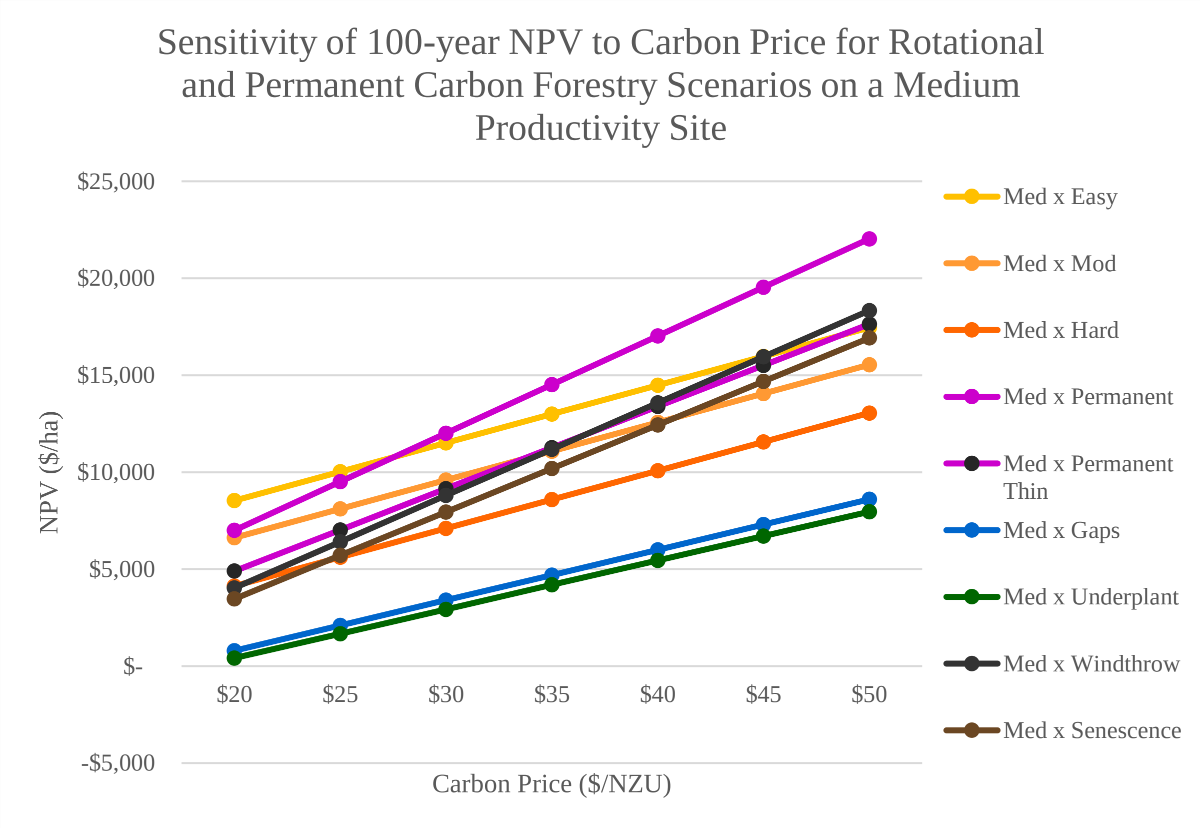

Figure 15: sensitivity of 100-year NPV to carbon price for rotational and permanent carbon forestry scenarios on a medium productivity site at the base log price

Similar trends can be seen on a medium productivity site with changing carbon price. However, rotational carbon forestry is more profitable in general compared to permanent carbon forestry. Unthinned and thinned permanent carbon forestry does not become more profitable than rotational carbon forestry on an easy TDWC site until the carbon price reaches approximately $27/NZU and $49/NZU compared to $24/NZU and $42/NZU on a low productivity site respectively. Additionally, only the windthrow scenario also becomes more profitable than rotational carbon forestry on an easy TDWC site above a carbon price of $45/NZU. Thinned permanent carbon forestry and the windthrow scenario remain similar in profitability at the base carbon price. However, thinned permanent carbon forestry becomes more profitable compared to the windthrow scenario as carbon price decreases and less so as carbon price increases. In terms of the managed transitional scenarios, both have a positive NPV at the lowest carbon price of $20/NZU and are most profitable at higher carbon prices.

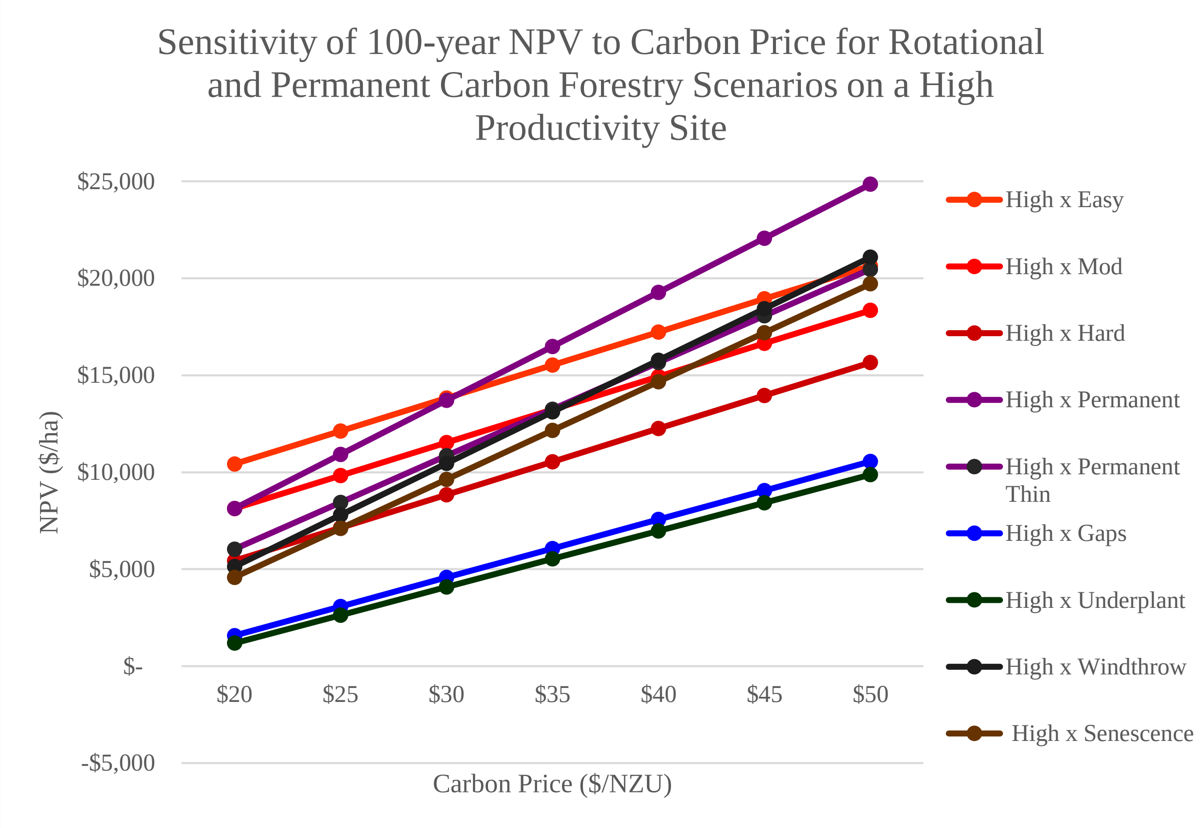

Figure 16: Sensitivity of 100-year NPV to carbon price for rotational and permanent carbon forestry scenarios on a high productivity site at the base log price

Again, similar trends in carbon price sensitivity can be seen on a high productivity site compared to other site productivities with permanent carbon forestry scenarios being the most sensitive to carbon price except for the managed transitional scenarios. Unthinned permanent carbon forestry does not become more profitable than rotational carbon forestry on an easy TDWC site until the carbon price is higher than $30/NZU. Thinned permanent carbon forestry has an NPV closer to that of rotational carbon forestry on a hard TDWC site at a carbon price of $20/NZU and doesn't become more profitable than rotational forestry on an easy TDWC site even at a carbon price of $50/NZU. The windthrow scenario is still more profitable than rotational forestry on an easy TDWC site at a very high carbon price of approximately $48/NZU. The NPV for both the canopy gap creation and underplanting managed transitional strategies from pine to native biomass is positive at all carbon prices.

Table 8: Breakeven carbon price of permanent carbon forestry with a structural thinning and rotational carbon forestry derived from Figures 14, 15 & 16

Site Productivity	TDWC Difficulty		
	Easy	Moderate	Hard
Low	$42	$27	$9
Medium	$49	$34	$14
High	$51	$35	$16

5. Discussion and Conclusions

5.1 Carbon Stock Profiles

Canopy closure can occur from 6-8 years within a plantation forest (Lambie, et al, 2018). The period of greatest carbon sequestration within a radiata pine stand is 5-10 years when growth rate is at a maximum. This period is also the least affected by discounting and the time value of money. In the thinned permanent radiata pine scenario, the first waste thinning down to 800 stems/ha is done at age 8 (section 3.1), disrupting the period of rapid carbon sequestration. However, it is not until the second waste thinning at age 11 down to 500 stems/ha that the effects of this more severe thinning significantly reduce carbon stock compared to unthinned permanent radiata pine forestry (Figure 5). The first canopy gaps created for native restoration occur when the radiata pine stand is 12 years of age (Table 6). This allows for the period of greatest carbon sequestration to occur without disturbance and for the cost of the first thinning to be further discounted, maximising value. Canopy gap creation mimics natural disturbance such as a large dominant canopy tree falling and increases light transmission to the forest floor, allowing the regeneration of native species (Forbes, et al, 2016). As a result, with each subsequent canopy gap creation event, pine biomass is reduced more significantly (Figures 1-4) and light transmission is increased, allowing for more prolific native regeneration.

Passive native regeneration within the canopy gap creation scenario (Figure 2) is more vigorous than that of the planted natives within the underplanting scenario (Figure 4). This is due to the assumptions made around the growth rate of the different types of native vegetation that will be regenerating within these scenarios (Appendix E). The native biomass used in the canopy gap creation scenario is a modification of the Carbon Look-up Table. The MPI indigenous Carbon Look-up Table assumes the regeneration of rapid growth, pioneer native scrubland species such manuka and kanuka in an open space (MPI, 2017). The more rapid growth of these species leads to more significant, earlier carbon sequestration of these in comparison to the slower growth of the shade tolerant species within the underplanting scenario (rimu, tōtara and kahikatea) and results in the higher carbon stock in the canopy gap creation scenario. However, the rate of increase in carbon stock of the dominant podocarp species within the underplanting scenario is greater year-on-year than that of the canopy gap creation scenario in later years. This suggests the peak carbon stock may be higher within the underplanting scenario beyond 100 years as podocarp species grow to be larger in stature, sequestering more carbon. The greater carbon stocks achieved by passive native regeneration within canopy gaps is a 'best case' scenario, however. On many New Zealand sites, underplanting will be required due to limited seed source availability (Forbes, et al, 2019) or unfavourable climatic conditions. As a result, underplanting will likely need to be undertaken to achieve a transition to a native forest.

Carbon sequestration by a pure radiata pine stand is substantial (Figure 5). Carbon stock achieved within 100 years is much more than that of the native biomass within the managed transitional scenarios due the more rapid growth rate of radiata pine when left untouched. Unthinned permanent carbon forestry represents a perceived scenario of blanket afforestation under high carbon prices. However, plant and leave forestry (1,000 stems/ha, untended) results in an unstable forest as high stockings increase susceptibility to windthrow (Knowles & Paton, 1989), the transmission of pests and disease (Munck, et al, 2016) and competition for resources, often leading to earlier senescence. The windthrow and senescence scenarios model the effects on carbon stock should these events occur. Under the windthrow scenario, there is a large carbon stock liability at 50 years despite native regeneration which would require the repayment of these NZUs previously earned but then surrendered under the ETS (MPI, 2020) (Figure 9). Should senescence occur and native vegetation is able to regenerate within the understorey, this native biomass prevents a significant carbon stock liability due to senescence.

5.2 Permanent and Rotational Forestry

On all sites, unthinned permanent carbon forestry is the most profitable scenario (Figures 8, 9 & 10). However, permanent carbon forestry with a structural thinning scenario is more realistic as this thinning increases the stability of the forest canopy making it less susceptible to windthrow and early senescence. This structural thinning is also the same regime as the rotational carbon forestry scenarios making these scenarios directly comparable in terms of the decision to harvest a forest for wood products or continue earning carbon credits through permanent forestry.

Permanent carbon forestry with a structural thinning is more profitable than rotational carbon forestry on a moderate and hard TDWC site across all site productivities. However, rotational carbon forestry on more difficult sites became more competitive with thinned permanent carbon forestry as site productivity increases. Even if windthrow or senescence were to occur in an unthinned permanent carbon forest, because these events are likely to occur so far into the future, the bulk of carbon sequestration has already occurred. The discounting effect also means the NZUs that need to be surrendered due to a decrease in total carbon stock have a lower present value than when they were earned through sequestration. As a result, the NPV of these scenarios remains high and competitive with rotational carbon forestry across all site combinations. The NPV of the windthrown unthinned permanent forestry scenario is very similar to that of thinned permanent carbon forestry across all site productivities. Should MPI no longer require the repayment of NZUs due to 'adverse events' such as windthrow or fire under the stock change accounting approach (MPI, ETS Improvements, 2020), permanent carbon forestry will be further incentivised as the risk due to these adverse events is mitigated.

As a result, a forest that is established under the ETS with a structural thinning would be more profitable if managed as a permanent carbon forest rather than as a rotational carbon forest on all site productivities, except on an easy TDWC site where the costs associated with harvesting, extracting and delivering wood to market are low.

5.3 Transitioning Pine Forests to Natives

The two managed transitional strategies from radiata pine to native forest through gap creation give positive NPVs across all site productivities at the base log and carbon price (Figures 8, 9 & 10). Only on a low productivity site, at the carbon price floor of $20/NZU, does the underplanting scenario have a slightly negative NPV. This is an important finding as usually; if native restoration were to be undertaken planting at 2,500 stems/ha in an open area without a nurse crop, NPV would be negative (Davis, et al, 2009), even with the aid of 1BT grants (Te Uru Rākau, Direct Grants, 2020) (Appendix B). This is due to the high cost of establishment for natives compared to pines (Table 3). Native seedling costs (Table 7) are higher due the need for planter bag protection during transport to avoid desiccation and the requirement by nurseries to grow stock directly from seed (Davis, et al, 2009). In comparison, radiata pine seedlings can be purchased from nurseries as bare root stock for $0.20-$0.50/plant depending on the level of genetic improvement, quantity ordered and how they were propagated (Davis, et al, 2009). In addition to the high seedling costs, native establishment also requires weed and pest control, a more specific planting technique and fencing to eliminate browsing animals (Davis, et al, 2009; Forbes, et al, 2016). These elements lead to significantly increased establishment and labour costs. Total establishment costs used in this analysis for natives underplanted within canopy gaps was $4,554/ha compared to $1,770/ha for the pine overstorey. Even the cost of fencing and an annual overhead including pest control in the passive regeneration within canopy gaps scenario ($2,347/ha) was more expensive than pine establishment.

Using a radiata pine forest as a nurse crop for native regeneration allows the costs of establishment to be significantly reduced, a smaller area per hectare of natives required to be established, increased revenue through rapid early carbon sequestration and more favourable conditions for native regeneration. This is in comparison to facilitating native regeneration passively or through direct planting in an open space.

Despite this however, across all site combinations the canopy gap creation and underplanting managed transitional scenarios still had the lowest NPV of all the scenarios. This is because enabling native regeneration remains a costly process and results in less carbon sequestration, even with a pine forest acting as a nurse crop.

The difference in NPV between these two managed transitional scenarios was within $500/ha across all site productivities. This is due to these scenarios having the same pine carbon stock profiles and the same fencing and pest control costs. The cost of fencing to exclude browsing ungulates is the majority of the establishment costs for native regeneration whether through passive facilitation or underplanting. The added cost of underplanting and the lower rate of carbon sequestration achieved by the native biomass results in a lower NPV for the underplanting scenario.

5.4 Log Price

Permanent carbon forestry scenarios – those which will not be harvested to sell logs – are not sensitive to log price. However, rotational carbon forestry is very sensitive to log price across all site productivities (Figures 11, 12 & 13). This is because the majority of the value of rotational forestry is determined by TDWC and the sale of wood products rather than carbon sequestration. The profitability and competitiveness of rotational carbon forestry compared to permanent carbon forestry increases as log price increases and vice versa.

Should average log price increase by approximately $24/t (+1.5 standard deviations), a landowner would be indifferent about whether or not to harvest a forest on a medium productivity, moderate TDWC site or continue sequestering carbon as a permanent forest. Above an average log price of $140/t (+2 standard deviations), all forests with a structural thinning would be more profitable as rotational rather than permanent carbon forests. Log price must increase less for rotational carbon forestry to become favoured over permanent carbon forestry as site productivity increases. This is because as site productivity increases, trees grow more rapidly in volume, sequestering more carbon and yielding more, larger diameter logs. The larger diameter as well as the taller trees enables more of the harvested stems to meet higher log grade requirements and fetch a higher price on higher productivity sites. As a result, the log price increase needed for rotational carbon forestry to breakeven with permanent carbon forestry is reduced on more productive sites.

In contrast, any decrease in log price results in permanent carbon forestry becoming more favourable compared to rotational carbon forestry. Should average log grade price decrease to $84/t (-1.5 standard deviations), all forests with a structural thinning would be more profitable if left as a permanent forest to sequester more carbon rather than be harvested for wood products due to the decreased value of rotational forests. Again, this effect is magnified by site productivity. As site productivity decreases, trees grow with less volume, sequester less carbon and yield fewer, smaller diameter logs. These poorer quality logs fail to meet higher log grade requirements of length and diameter and fetch lower prices. As a result, the reduction in log price needed for permanent carbon forestry to breakeven with rotational carbon forestry decreases on less productive sites.

On all site productivities, at an exceptionally low average log grade price of $61/t (-3 standard deviations), the canopy gap creation and underplanting managed transitional scenarios were more profitable that rotational carbon forestry on a hard TDWC site. This is because at -3 standard deviations from the mean log price, the value of the harvested timber under rotational forestry is so low, NZUs earned by the managed transitional scenarios are worth more at a carbon price of $35/NZU. This is despite canopy gap creation causing the carbon sequestration by pine biomass to be significantly reduced and the slower carbon sequestration of the native biomass replacing the pine biomass.

5.5 Carbon Price

The results of this analysis are highly sensitive to carbon price (Figures 14, 15 & 16). Permanent carbon forestry, except the canopy gap creation and underplanting scenarios, are more sensitive to carbon price than rotational carbon forestry scenarios as 100% of their revenue is derived from earning NZUs through sequestration. This is in comparison to rotational carbon forestry where approximately 60% of present value of one rotation is achieved through carbon sequestration under the average accounting approach. Unthinned permanent carbon forestry scenarios (including windthrow and senescence) are more sensitive to carbon price than thinned permanent carbon forestry scenarios (including canopy gap creation and underplanting). This is because thinning the pine forest interrupts carbon sequestration, often decreasing total carbon stock and reducing the potential revenue that can be obtained through increases in total carbon stock.

The canopy gap creation regime achieved through thinning in the managed transitional scenarios significantly limits the ability of the pine biomass to sequester carbon. The sequestration of the native biomass replacing the pines is comparatively much slower (Figures 1 & 3). As a result, the canopy gap creation and underplanting scenarios are about as sensitive to carbon price as rotational carbon forestry across all sites.

Sensitivity to carbon price increases as site productivity increases; although more dramatically for permanent carbon forestry, except the managed transitional scenarios compared to rotational carbon forestry. This is because as site productivity increases, trees can grow with more vigour to a greater volume more quickly. This increased growth rate leads to greater carbon sequestration and allows more revenue to be derived from earning NZUs, resulting in a higher sensitivity to carbon price. In general, sensitivity to carbon price is determined by the ability of a forestry scenario to sequester carbon and how dependent the value of that scenario is on carbon sequestration.

One important implication that can be derived from Figures 14, 15 & 16 is the breakeven carbon price between permanent carbon forestry with a structural thinning and rotational carbon forestry on a low, medium and high productivity site summarised in Table 8. This is the carbon price at which a landowner on a certain site would be indifferent about harvesting a structurally thinned pine forest or leaving it to sequester more carbon as a permanent forest.

On a hard TDWC site, the carbon price would have to be below the current carbon price floor of $20/NZU to make the NPV of rotational carbon forestry breakeven with permanent carbon forestry. Even at these exceptionally low carbon prices, the value of the carbon sequestered by a permanent forest is equal to that of the timber that could be harvested, extracted and delivered from this difficult site under rotational carbon forestry. Under the current ETS, it is not possible for the carbon price to drop below $20/NZU meaning on a hard TDWC site, rotational carbon forestry will not be more profitable than permanent carbon forestry due to a drop in carbon price, irrespective of site productivity.

On a moderate TDWC site, the breakeven carbon price is at or below the current carbon price of $35/NZU (OMF Financial, 2020) (Appendix A). This means the carbon price would have to decrease on a moderate productivity site to devalue carbon sequestration and make a structurally thinned forest more profitable when managed as a rotational carbon forest rather than a permanent carbon forest.

On an easy TDWC site, the breakeven carbon price is above the current carbon price. This means that the carbon price would have to increase by at least $7/NZU on a low productivity site for a structurally thinned forest to be kept as a permanent carbon forest rather than harvested as a rotational carbon forest. On an easy TDWC and high productivity site, carbon price would have to increase above the 2021 cap of $50/NZU (not currently possible) for a structurally thinned forest to be kept as a permanent carbon forest rather than harvested. This increase in carbon price is required to increase the value of NZUs earned by a permanent forest to be above the value of easily harvesting the same productive forest for wood products at the base log price.

5.6 Conclusions

This analysis has provided answers to, and has allowed conclusions to be made about, the research questions:

1. Permanent carbon forestry is often more economically viable than rotational carbon forestry at a carbon price of $35/NZU. This is the case on all sites when the permanent carbon forest is unthinned. The profitability of permanent carbon forestry in comparison to rotational carbon forestry increases with carbon price. Rotational carbon forestry becomes more competitive with permanent carbon forestry as carbon price and TDWC difficulty decreases and log price and site productivity increases.
2. The managed transitional strategy chosen to achieve native restoration will have an NPV significantly less than that of permanent or rotational carbon forestry under any combination of site productivity and TDWC difficulty and under any likely carbon price, except under an exceptionally low log price when transitioning a radiata pine forest to a native forest will be more profitable than managing it as a rotational forest (approximately 0.1% of the time).
3. The managed transitional strategy chosen to achieve native restoration, be it canopy gap creation or underplanting, will not significantly affect NPV.

In general, only under an exceptionally low log price will permanent carbon forestry with the added benefit of native restoration become more favourable than rotational carbon forestry from a purely monetary perspective. However, if a landowner desires a truly permanent native forest, canopy gap creation or underplanting within a radiata pine carbon nurse crop can achieve this while still making a return on the landowner's investment.

6. Limitations

This dissertation is not based on data that has been directly measured. This is due to a distinct lack of long-term radiata pine nurse crop data available in New Zealand as discussed in the literature review (section 2). As a result, the analysis performed in this dissertation makes several assumptions in the construction and use of the financial model. Although these assumptions have been documented and justified in the methods (section 3), the results themselves should not inform any forestry investments or long-term harvest or afforestation decisions without consulting other sources of information. Models, by definition, are an abstract representation of reality and as a result are inherently flawed. The sites in this analysis are theoretical and were used to represent a range of typical sites throughout New Zealand. Specific sites in New Zealand may differ significantly in one or more of the measures used within this analysis and will be unique in their own right. As a result, it is important to make decisions based on data from the forest concerned.

The sensitivity analysis has attempted to account for changes in log and carbon price. However, due to social, political, market or environmental factors out of the industry's control such as changes to, or the abolishment of, the ETS or climate change effects, results will likely vary within the 100-year timeframe. This modelling does not make assumptions about what may happen beyond the 100-year horizon. However, it would be valuable to explore the success of the transitional strategies beyond 100-years in terms of total carbon stocks and the type of resulting forest. Despite the assumptions made, this dissertation still provides some important and credible results from which conclusions and recommendations can be made about permanent and rotational carbon forestry in the ETS.

Further research is recommended in the form of more sophisticated LINKNZ type modelling over a longer time period based on real measurement data. The installation and maintenance of PSPs within permanent carbon forests using the managed transitional strategies described within this dissertation (or some variation of them) in New Zealand is essential for this to happen. Data from these trials could be used as inputs for the financial model used in this, or some other analysis, to obtain more representative results.

7. Recommendations

Despite the high NPV under all site combinations, permanent carbon forestry is not recommended across all sites, thinned or unthinned. This is because the New Zealand public does not want to see blanket afforestation of radiata pine on all available land (Chalmers, 2019; Eder, 2019). This is also not conducive with the goals of 1BT to enhance natural landscapes and increase biodiversity and tourism (MPI, 1BT, 2020). The increased funding for native afforestation under 1BT in comparison to exotic afforestation exemplifies this (Te Uru Rākau, Direct Grants, 2020) (Appendix B). In addition, radiata pine forests cannot be considered permanent in comparison to a structurally and compositionally diverse successive native forest which has increased longevity, is less susceptible to windthrow and senescence and provides greater ecosystem services. Instead, on the poorest of sites where permanent carbon forestry is most profitable and where there is a native forest nearby, it would be preferable to transition these forests into natives. These forests could also be used for permanent erosion control where the steep land is too risky to harvest safely and in an environmentally conscious manner.

Rotational carbon forestry is still an option for landowners looking for a more short-term return on investment on good sites. This is when profitability is the main objective over just one rotation. However, if a compositionally and structurally healthy permanent native forest is desired in the long-term, the managed transitional strategies can achieve this and still provide a financial benefit for the landowner.

To achieve a permanent native forest, canopy gap creation followed by underplanting may be required. This is in contrast to canopy gap creation alone followed by passive native regeneration from a nearby seed source within the understorey. Underplanting will likely be required on many New Zealand sites where a viable seed source is not within dispersal range or where a native seed bank is not present within the soil.

The key recommendation of this dissertation is that the new permanent forestry activity to be implemented in 2023 (MPI, ETS Improvements, 2020) as part of the ETS should allow for canopy gap creation through thinning without being considered harvesting. Under the now redacted PFSI, a waste thinning down to 80% of the preharvest basal area was permitted (MPI, PFSI, 2015). Any subsequent harvest was limited to the basal area removed during the first harvest or to retaining 80% of the original pre-harvest basal area, whichever was greater (Appendix G) (MPI, PFSI, 2015). The canopy gap creation regime used in this analysis (Table 6) would not have fit within these parameters and would have been considered clear-fell harvesting under the PSFI. This would have broken the landowner’s 50-year covenant with the government and subjected them to financial penalty in the form of surrendering all NZUs earned, plus interest (MPI, PFSI, 2015). Canopy gaps created from thinning down to 80% of the original forest basal area are unlikely to achieve effective native forest restoration within 100 years. As a result, it is paramount that MPI allow a managed transition through canopy thinning such as the regime described in this dissertation to enable permanent carbon forests to be transitioned to natives while earning NZUs under the ETS. This will be a cost-effective way for a landowner to establish a native forest and deliver on the climate change mitigation, environmental, social and economic goals of the 1BT and ETS.

Permanent radiata pine forests offer the New Zealand public the opportunity to have the best of both worlds. That is the rapid carbon sequestration at low cost of radiata pine; along with the environmental and societal benefits of long-term native restoration.

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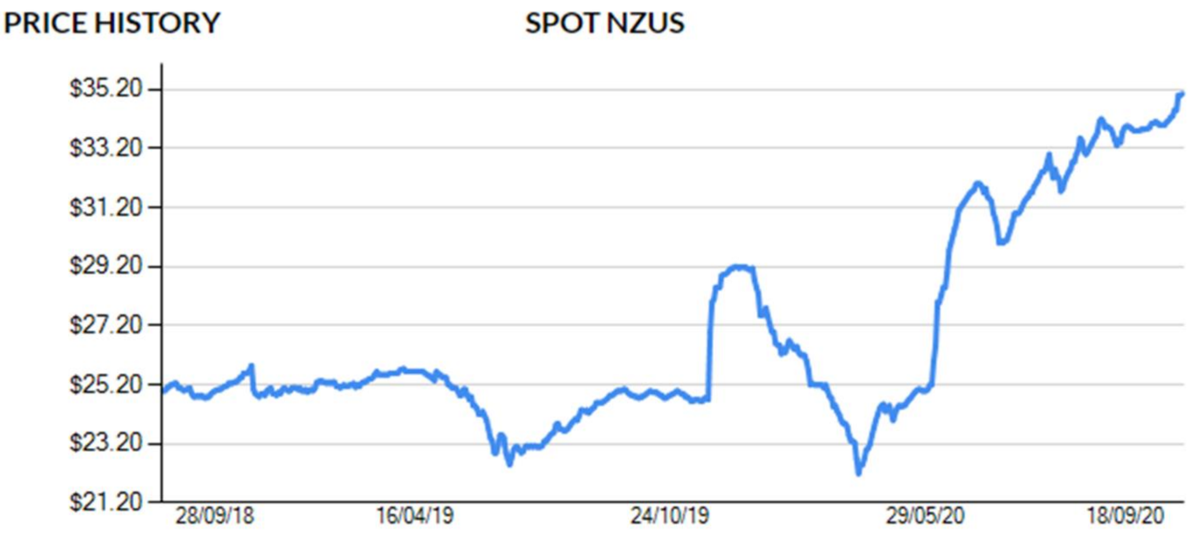
9. Appendices

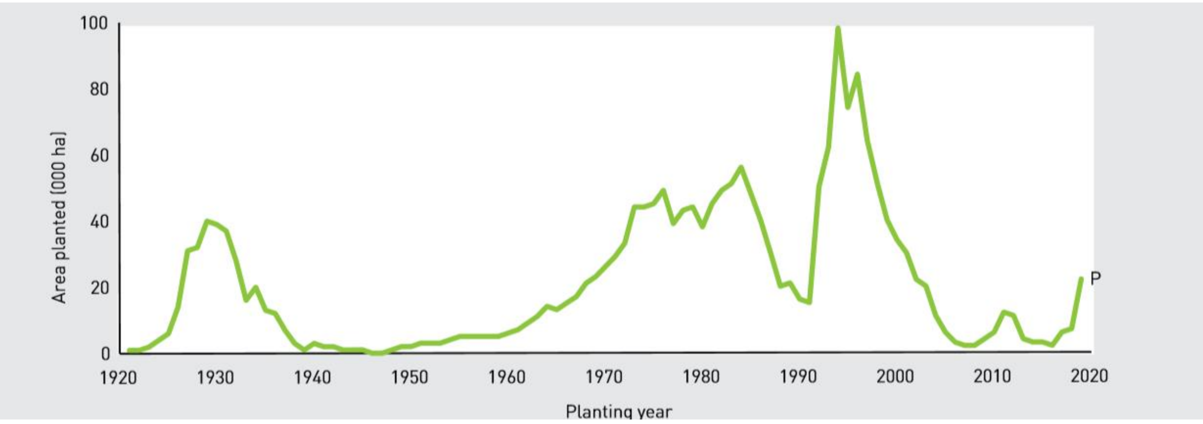
Appendix A: Carbon price as at September 2020 (OMF Financial, 2020)



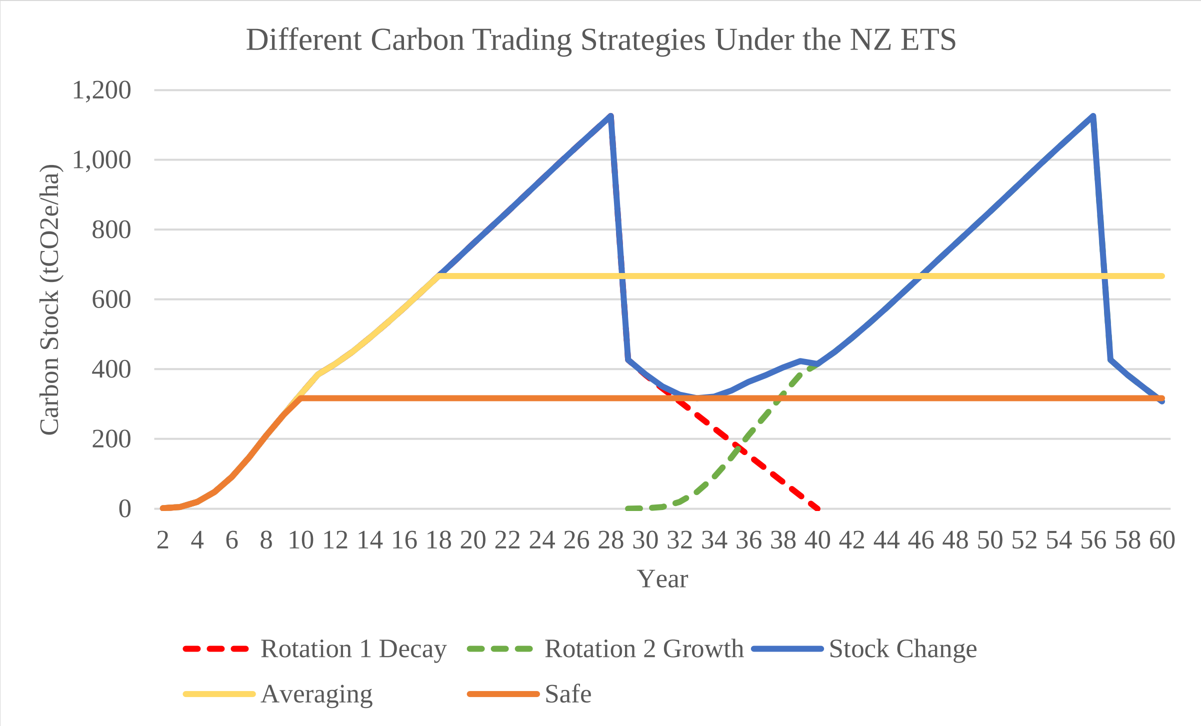
Appendix B: Afforestation grants under 1BT (Te Uru Rākau, Direct Grants, 2020)

Category	Size	Base rate/hectare	Available top-ups /hectare: Priority land: Erosion-prone land	High land preparation costs	Fencing	Ecological restoration
Native Planting	1 – 300 hectares	$4000	Up to $500		Up to $500	Up to $2000
Native Reversion	5 – 300 hectares	$1000	Up to $500		Up to $500	NA
Mānuka/Kānuka Planting	5 – 300 hectares	$1800	Up to $500		NA	NA
Exotic Planting	5 – 300 hectares	$1500	Up to $500		NA	NA

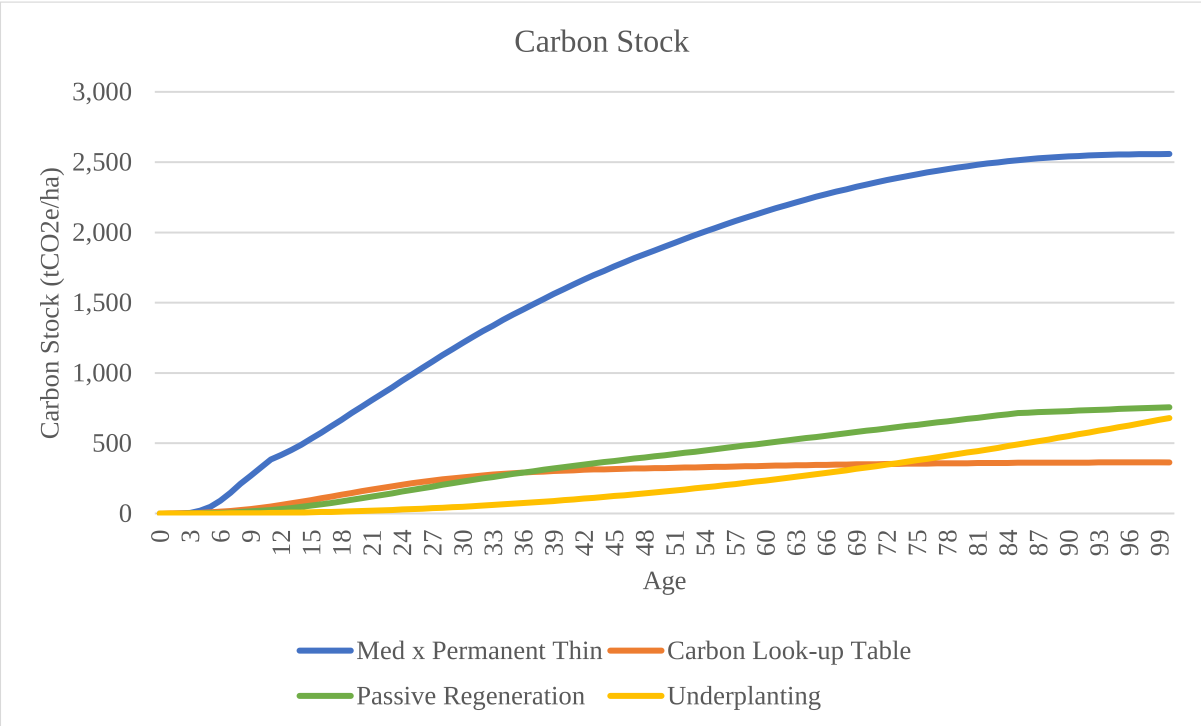
Appendix C: New land planted in production forest in New Zealand (MPI, NEFD, 2019).



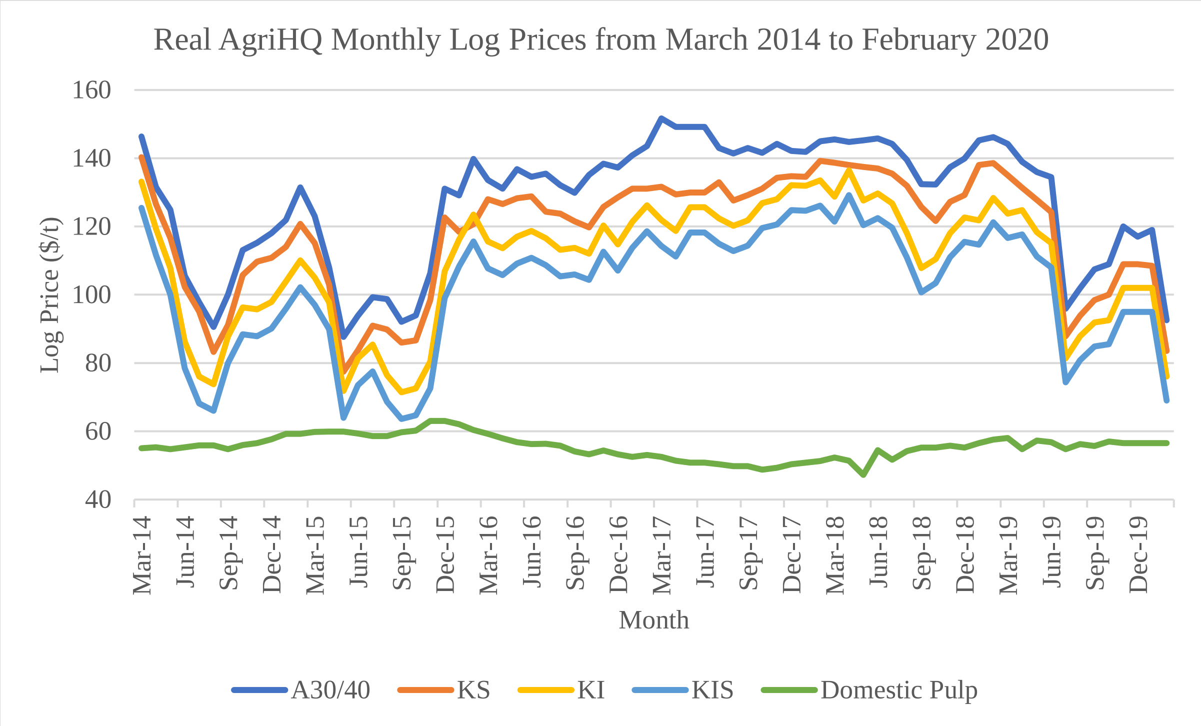
Appendix D: Different carbon trading strategies under the ETS (two rotations)



Appendix E: Modification of the MPI Native Carbon Look-up Table for natives used for passive understorey regeneration compared to the original, pine biomass and underplanting biomass



Appendix F: Real AgriHQ Monthly Log Prices from March 2014 to February 2020



Appendix G: An example of harvesting allowed under the PFSI (MPI, PFSI, 2015)